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DEVELOPMENT OF A MULTICHANNEL, ULTRASONIC TELEMETRY SYSTEM FOR THE STUDY OF SHARK BEHAVIOR AT SEA

by

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13. ABSTRACT

A telemetry system is described which is capable of monitoring the behavior of free-swimming sharks in the natural environment. The transmitters emit 10 msec ultrasonic pulses at 40 kHz, have a life of up to one week, and a maximum range of over 3 miles. The units can transmit one, four, or eight channels of information using either of two types of electronic multiplexing: one interpulse interval/channel, or fixed time/channel. The pulse rate varies with the value of resistive sensors and ranges from .5/sec to 5/sec. Sensors are described for measuring depth, swimming speed, compass heading, ambient light, and temperature. Single channel and multichannel transmitters have been used successfully and recovered from pelagic species (blue sharks, Prionace glauca) and from bottom-dwelling species (angel sharks, Squatina californica).

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INTRODUCTION

This initial report describes the development of a practical system for telemetering several aspects of the behavior of unrestrained sharks in their natural environment. The primary research objective for this system is to monitor more or less continuously for periods of up to several day-night cycles those variables indicating changes in behavior. In contrast to the much simpler and smaller units, often without sensors, which have been used in the past for animal tracking studies, this objective required a relatively powerful and complex transmitter incorporating several sensors and associated switching components.

Previous studies

Almost all of the earlier ultrasonic tracking studies involved the use of transmitters which acted as simple

*Telemetry of shark behavior at sea constitutes one phase of ONR contract N00014-68-C-0318, "FIELD INVESTIGATIONS OF SHARK BEHAVIOR," D.R. Nelson, principal investigator.

acoustic beacons. It is only recently that researchers have employed sensors in their transmitting packages. Baldwin et al. (1969) have developed and experimented with single-channel units capable of transmitting depth information, EKG'S, and EMG'S of marine mammals. Carey et al. (1971) have been successful in monitoring surface and deep body temperatures of bluefin tunas, Thunnus thynnus, while tracking at least one individual for over two days and a distance of 130 miles. Their transmitter was dual-channel, switching alternately between two temperature sensors at one-minute intervals. Other researchers, using transmitters without sensors, have attempted to gain indirectly additional data such as swimming speed and depth through the use of sophisticated (and expensive) receiving gear, e.g., sonar systems with visual displays. Yuen (1971) tracked two skipjack tuna, Katsuwonus pelamis, one for seven days, using a 50 KHz beeper. Although his transmitters contained no sensors he indirectly calculated approximate depth (from hydrophone angle) and swimming speed (distance traveled/time). As he points out, the accuracy of the latter approximation decreases as the fish's swimming deviates from a straight line, e.g., the fish may be swimming rapidly in tight circles (perhaps during feeding) and no movement would be detected.

Mitson and Storeton-West (1971) have constructed a limited range 300 KHz tag which contains receiver and transmitter sections used in a transponding mode. Plaice, Pleuronectes platessa, tagged with their unit have been successfully tracked using high resolution, electronic sector scanning sonar. With their system it is possible to determine the distance the tagged individual is from the tracking vessel and also its position with respect to the bottom.

Young et al. (1972) have developed a short range (220 meter) sonic tag which is capable of transmitting a fish's activity level (locmotion) as a frequency modulation. Their preliminary work was done with brown trout, Salmo trutta, in a small loch in Scotland.

To date there are only two published studies of ultrasonic transmitters being used on sharks. The earlier study (Bass and Rascovich, 1965) utilized a 38 KHz transmitter (10¼ in. long and 2½ in. O.D.) which weighed 34 ounces in sea water. This unit had a range better than two miles and was used to track one sandbar shark, Carcharhinus milberti, and one hammerhead shark, Sphyrna zygaena, as well as three individual tunas, Thunnus thynnus. Their study provided only locational data and no individual was tracked for more than four hours. Thorson et al. (1969) studied the movement of bull sharks, Carcharhinus leucas,

from the Caribbean Sea through the San Juan River into Lake Nicaragua. His system used a long-life 74 KHz sonic tag in conjunction with several automated monitoring devices placed at strategic locations.

The projects using perhaps the greatest number of sonic tags are those studying the movements of salmonids, (Trefethen et al., 1957), (Johnson, 1960), (Novotny and Esterberg, 1962), (Hallock,et al., 1970), (Hasler et al., 1970), (McCleave and Horrall, 1970), (McCleave and LaBar, 1972). For a detailed list (88 entries) of people and projects involved in the biological applications of underwater telemetry see Stasko (1971).

A review of the literature indicated that a transmitter of the type desired for our shark behavioral studies was not available and would have to be developed. We compiled the specifications required to meet our research objectives and adopted the following initial guidelines:

Range: Relatively great; minimum of one mile in the ocean

Life: Moderate; capable of at least several day-night cycles

Size: Moderate; small enough to be easily carried by sharks as small as three to four feet in length

Operating conditions: Capable of withstanding the pressure and temperature extremes found at depths of several hundred feet

Data channels: Minimum of three channels of information giving status of depth, temperature, and swimming-speed sensors

Method of application: Capable of relatively atraumatic application underwater by divers

Cost: Low enough to be expendable (although recovery may be attempted when possible), component cost not to exceed $50-100/unit

The possibility of commercially contracting such a development was considered but it soon became apparent that the cost would be prohibitive. The development of a transmitter and suitable sensors was therefore undertaken as part of the present ONR contract. The transmitters we are now using (which meet or exceed our initial specifications) are the result of a considerable developmental effort, some of which is reviewed here in order that this information may benefit others in the early stages of similar projects.

EARLY TRANSMITTER DESIGNS

The Mark I transmitter

Initial tests were made using a simple push-pull squegging oscillator (Fig. 1) modified from that shown by Mackay (1968). Multichannel capability was to be achieved by varying three characteristics of the transmitted signal: pulse rate, pulse length and frequency. Each factor was to vary dependent on the state of the sensor controlling that

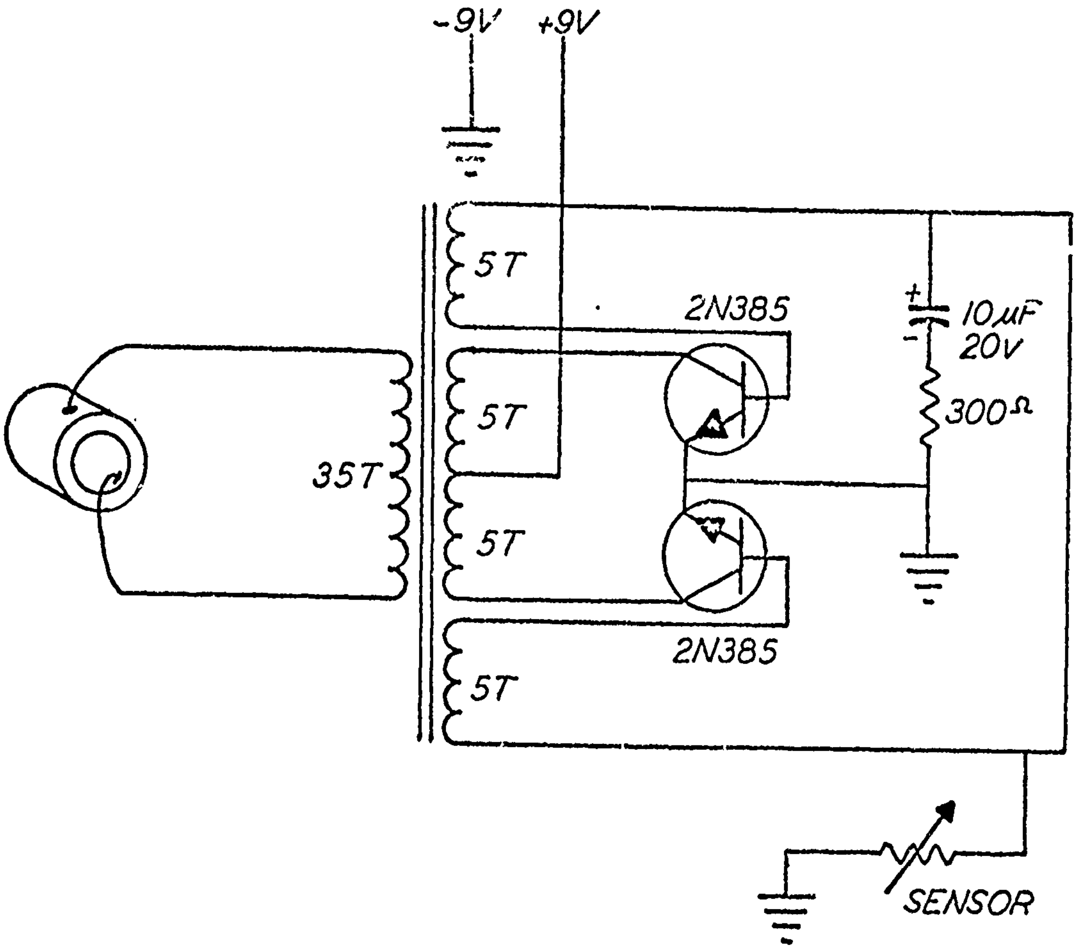


Figure 1. Schematic of Mark I transmitter (modified from Mackay, 1968; p 299).

function. An experimental tag of this design (without sensors) was constructed using a barium titanate (60 KHz) transducer.

The signal from the Mark I transmitter could be received at a distance of one-quarter mile by a Smith-Root TA-25 receiver equipped with a hydrophone (a duplicate 60 KHz BT ceramic) mounted in a parabolic reflector. The range was less than anticipated but the most serious drawback was the inability to encode data as previously planned. The carrier frequency was dependent on battery voltage, the pulse length interacted with pulse rate, and the pulse rate varied with temperature and other factors because of changes in reflected loading on the output transformer. It became obvious another method of encoding data had to be used. Although it would necessitate a method of commutation for multichannel capability, it was decided to vary only one characteristic of the signal, that of pulse rate. With this consideration, development of a more powerful, more stable single-channel transmitter began with the intention of later developing the necessary channel-switching capability.

The Mark II transmitter

One change made during the development of this model was to change the barium titanate transucers which resonate

at 60 KHz to lead zirconate titanate (PZT) transducers which resonate at 40 KHZ. The PZT element was to have greater transmitting efficiency and, in addition, 40 KHz was regarded as a better frequency for relatively long range transmissions considering the compromise between less attenuation with distance (desirable) and greater ambient noise (undesirable). The new PZT ceramics, however, caused a serious matching incompatability with the newly designed circuit. The problem was especially evident at low temperatures when the viscosity of the castor oil (used as an acoustic coupler) increased the mechanical loading on the PZT element to the point of actually stopping the oscillator. Although temperature limitations made this design unsuitable for the colder waters off California it was satisfactory for warmer tropical waters. During a stay at the Lerner Marine Laboratory, Bimini, Bahamas, several nurse sharks, Ginglymostoma cirratum, were tagged with single-channel depth transmitters of this design. The Mark II transmitter (Fig. 2) had improved frequency stability with respect to voltage fluctuations and provided a range of one-half mile in open water. This, however, was not always a workable range because the nurse sharks often entered underwater caves which acted as sound baffles making the signal directional and reducing the acoustic energy in the surrounding waters.

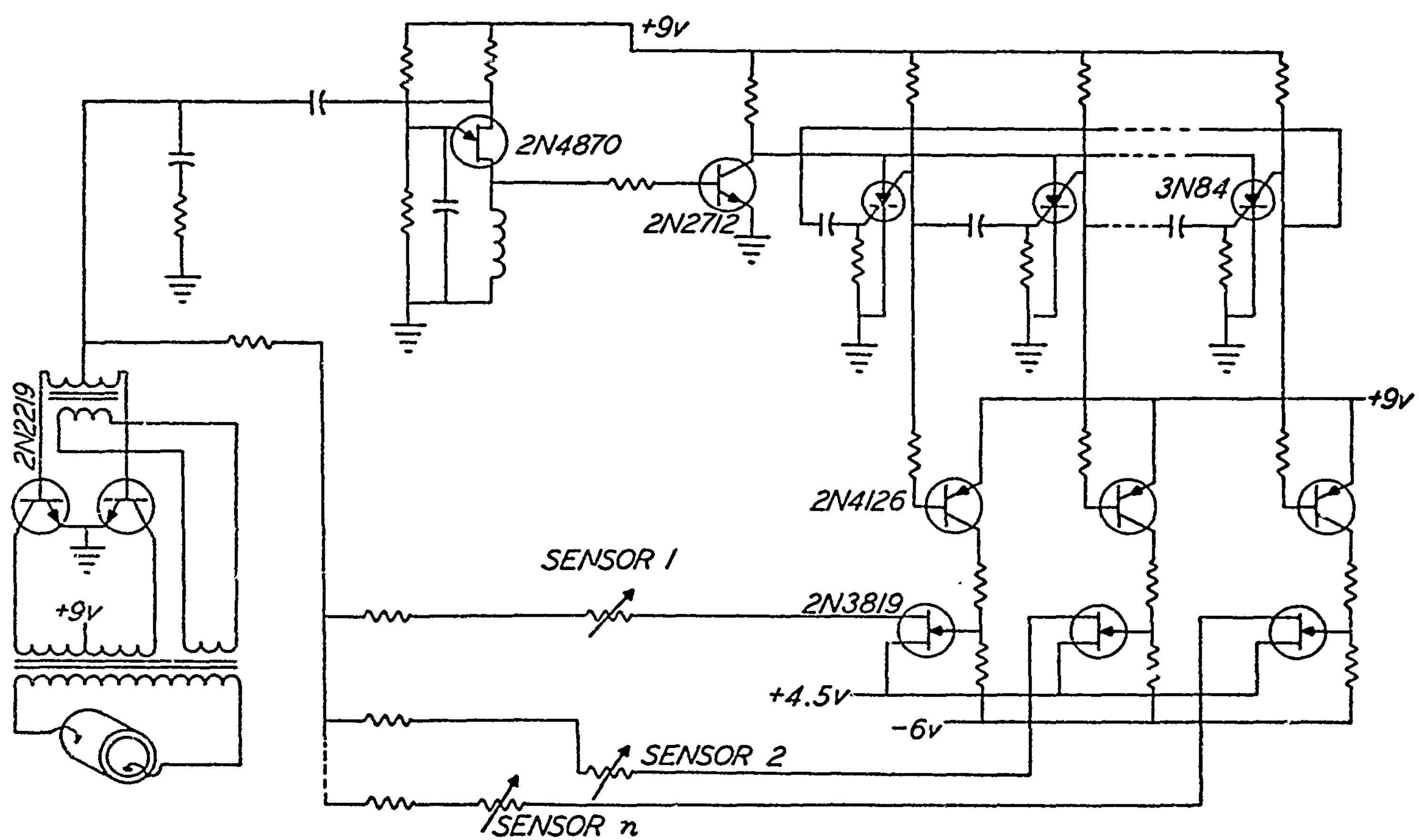


Figure 2. Schematic of Mark II transmitter and early type multiplexer (designed by H. Carter).

A four-channel electronic multiplexer (Fig. 2) utilizing discrete solid-state components was designed and built for the Mark II transmitter. Three channels were to be used for data and the fourth channel for reference and calibration. Each channel was on until it triggered a single pulse. By encoding in this manner the data for channel one was the time period between the reference pulse and the pulse of channel one; the data for channel two was the time between the pulse of channel one and the pulse of channel two, etc.

Although the multiplexer worked well on a breadboard, circuit reliability problems occurred in the actual miniaturized version. Because of the multiplexer difficulties, the transducer matching problem and the desire for still more range and a more stable frequency and pulse rate, the concept of using a basically simple transmitter circuit was dropped and a complete redesign was undertaken employing integrated circuits of the C/MOS type which had not been available earlier.

DESCRIPTION OF PRESENT SYSTEM

The Mark III transmitter

The present transmitter circuitry (Figs. 3,4) represents a complete redesign, aimed at solving the problems

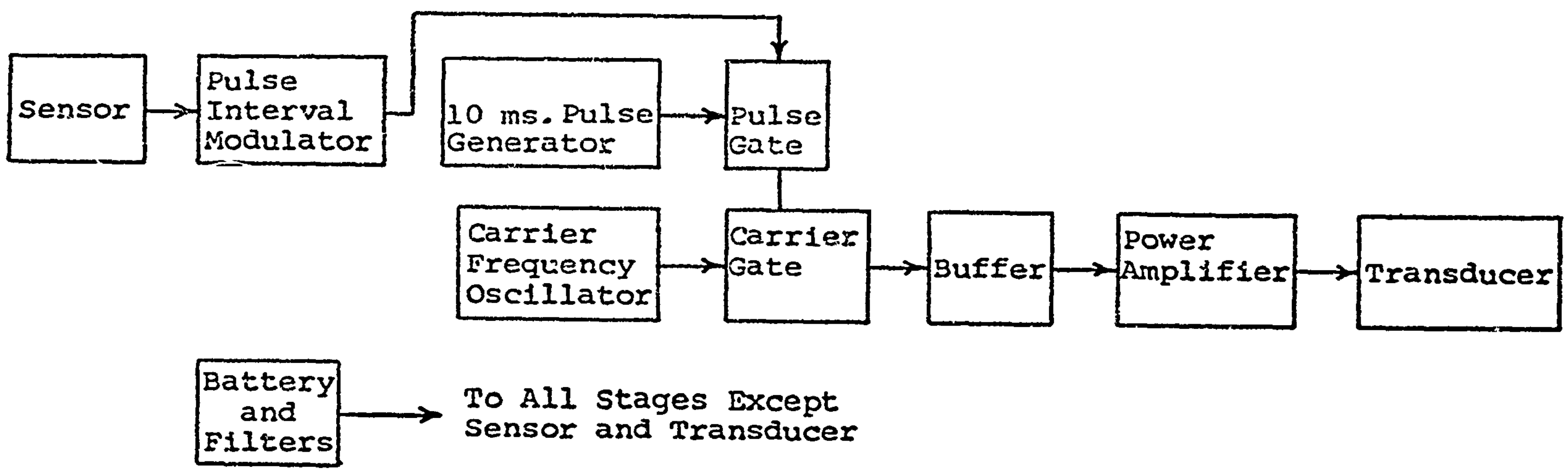


Figure 3. Block diagram of basic Mark III transmitter (single-channel version).

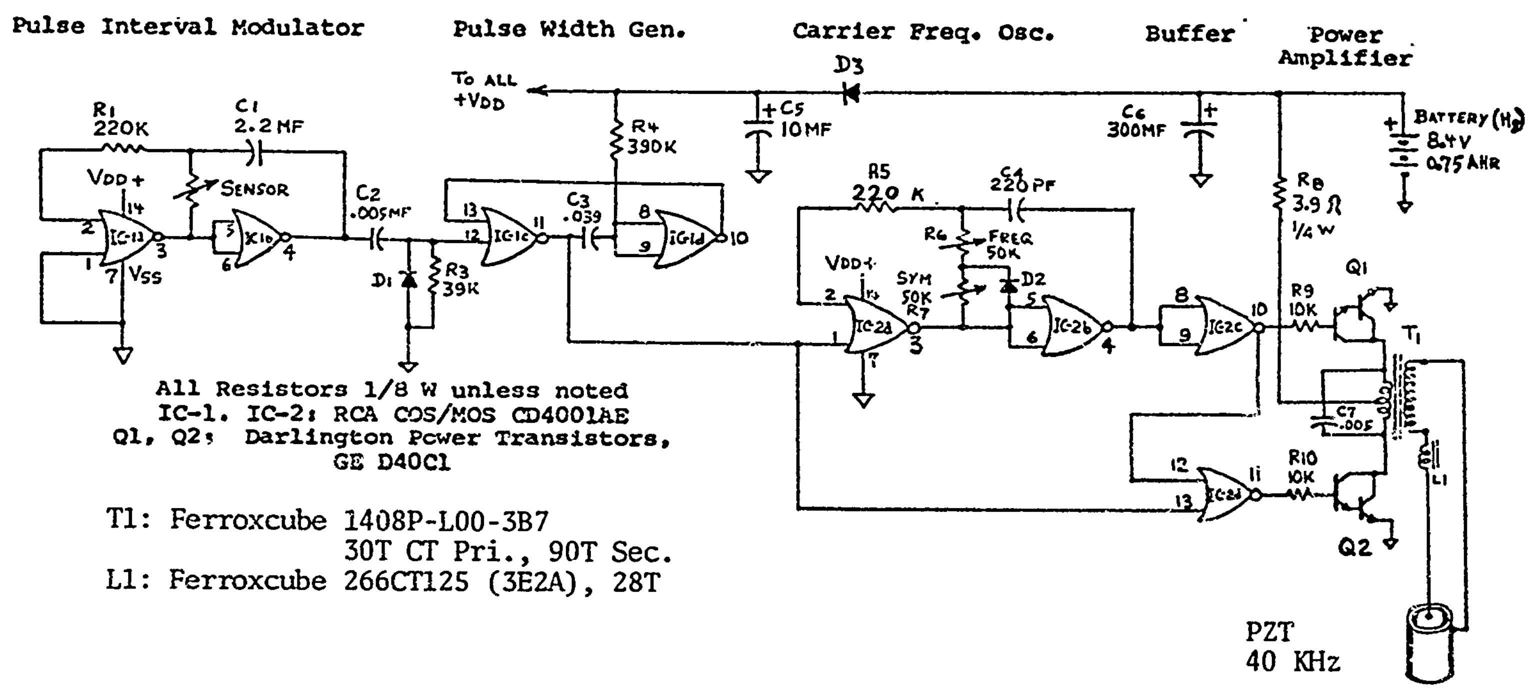


Figure 4. Schematic diagram of basic Mark III transmitter (single-channel version).

encountered in the earlier models. Although more elaborate, this design has proven much more reliable, more stable, and more powerful. The basic design can be used as a single-channel device employing one sensor or as a multichannel device with as many as seven sensors.

Specifications:

Range: maximum measured thus far under good environmental conditions, 3.2 statute miles; for clear recordable signal under good conditions, 2.0 mi.; for clear recordable signal under average conditions, 1.5 mi.

Life: approx. 150 hours until unit stops operating (when battery drops to 3.5 v.); approx. 100 hours until battery drops to 6.5 v., representing a drop of 25% in acoustic pressure output (using 8.4 v., 750 mah mercury battery and an average pulse rate of 3/second)

Frequency: nominal 40 KHz, tunable from 25 KHz to 50 KHz (greater with slight component change), downward drift approx. 800 Hz/initial 2-volt battery drop*

Power Output (at 8.4 v.): 6 watts electrical at PZT transducer input, measured acoustic pressure level at 1 meter +164 dB re: 1 N/m^2 (+64 dB re: 1 dy/cm^2)

Power Consumption (at 8.4 v.): during pulse, 700 ma; during interpulse period, 3 ma

Pulse Rate: 5/sec. to .5/sec., representing a sensor resistance of approx. 50K ohms to 500Kohms respectively

Pulse Length: 10 msec., adjustable over a wide range, rectangular pulse envelope

*An optional crystal oscillator for constant frequency is described by Ferrel (1972).

Waveform (at transducer): adjustable to sinusoidal

Data Channels: up to eight, multiplexed as 1 pulse interval/channel or as fixed time/channel, one channel reserved for calibrate-reference

Operating Conditions: to a depth of at least 1000 ft., to below 0°C.

Size: approx. 6 in. long, 1.3 in. dia.

Weight: approx. 8.4 oz. in air, 3.5 oz. in seawater, depending on sensors and battery type

Cost: see appendix

Basic circuitry:

The present basic transmitter (designed by H. Carter) is considerably different from the earlier Mark I and Mark II versions, which were primarily squegging oscillators. The frequency of a squegging oscillator is dependent upon its feedback transformer which is also used to couple the oscillator output to the transducer. Variations of the immediate acoustic surroundings of the transducer, e.g., changes with temperature in viscosity of the coupling oil, will change its mechanical loading which when coupled back to the frequency dependent transformer results in unacceptable frequency shifts. The Mark II unit partially solved the problem of frequency excursions by using a separate transformer for coupling the transducer. The PZT crystal, however, was still not sufficiently isolated from the carrier frequency oscillator. The Mark III transmitter employs a

buffer stage and a power amplifier to adequately isolate the ceramic transducer.

By incorporating the newly developed C/MOS type digital integrated circuits into the design, with their microwatt quiescent power requirements, relatively long transmitter life is obtained without excessively large batteries. The integrated circuits also offer excellent temperature and pressure stability in addition to their small size, low price, and complex-function capabilities. The Mark III transmitter utilizes integrated circuits in all but its output stage which incorporates silicon power transistors.

Unlike the earlier transmitter, the Mark III units can be tuned for frequency and adjusted for wave-form symmetry by using two trimpots which before final packaging are replaced by fixed resistors of the appropriate value.

Basically, the single-channel circuit consists of a resistive, sensor-controlled pulse interval modulator which actuates a ten-millisecond pulse-length generator which turns on the carrier-frequency oscillator which is then fed to the buffer and power amplifier stages and finally to the output transducer. A more complete description of circuit operation, including laboratory tests relative to voltage, temperature, and pressure, is given by Ferrel (1972).

Electronic multiplexer:

This represents a complete redesigning (by D. Ferrel) of the earlier Mark II multiplexer and incorporates C/MOS integrated circuits for increased reliability, size reduction and ease of construction (Figs. 5,6). The new multiplexer, unlike the old design, does not require an alternate power supply with several voltages but operates directly off the same battery powering the transmitter itself. This design also offers the advantage of flexibility, being easily changed between a four-channel mode and an eight-channel mode by simply adding or removing one integrated circuit.

In the eight-channel version, seven sensors and the reference resistor are sequentially connected to the pulse-interval modulator by eight multiplexer switches (in two I.C. chips) which are controlled by the multiplexer sequential controller (in a third I.C. chip). The four-channel version requires four fewer switches (one less I.C. chip). The multiplexer sequential controller advances by one count for each pulse of the pulse interval modulator, and automatically resets to channel one at the end of each sequence. These multiplexers alternately sample each of the sensors' resistances for one interpulse duration in the same manner as the Mark II multiplexer (Fig. 7). The first channel is used as a marker to identify channel

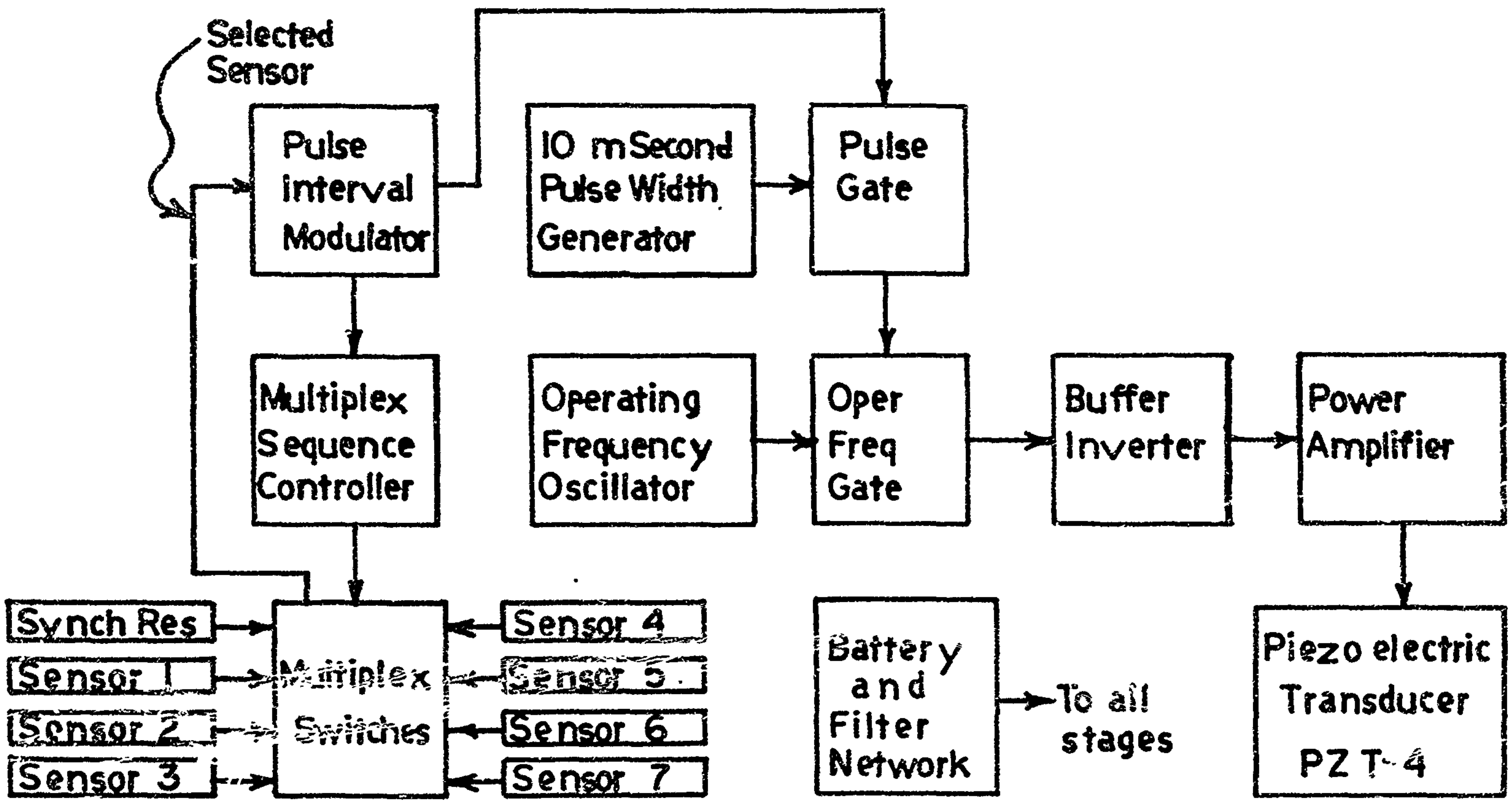


Figure 5. Block diagram of Mark III transmitter with electronic multiplexer (8-channel version).

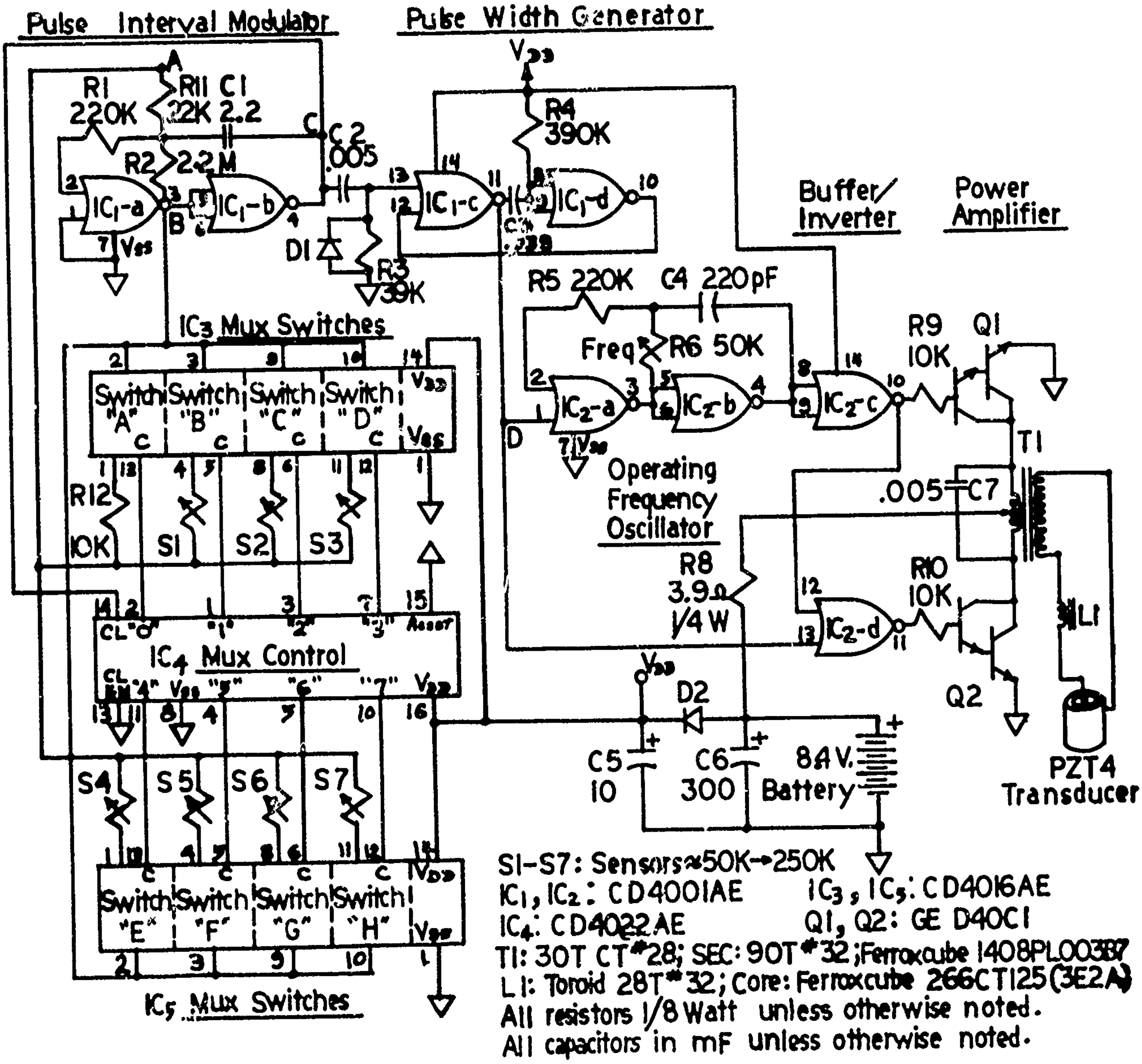


Figure 6. Schematic diagram of Mark III transmitter with electronic multiplexer (8-channel version). Can be reduced to 4 channels by removing IC-5 and connecting pins 11 and 15 on IC-4.

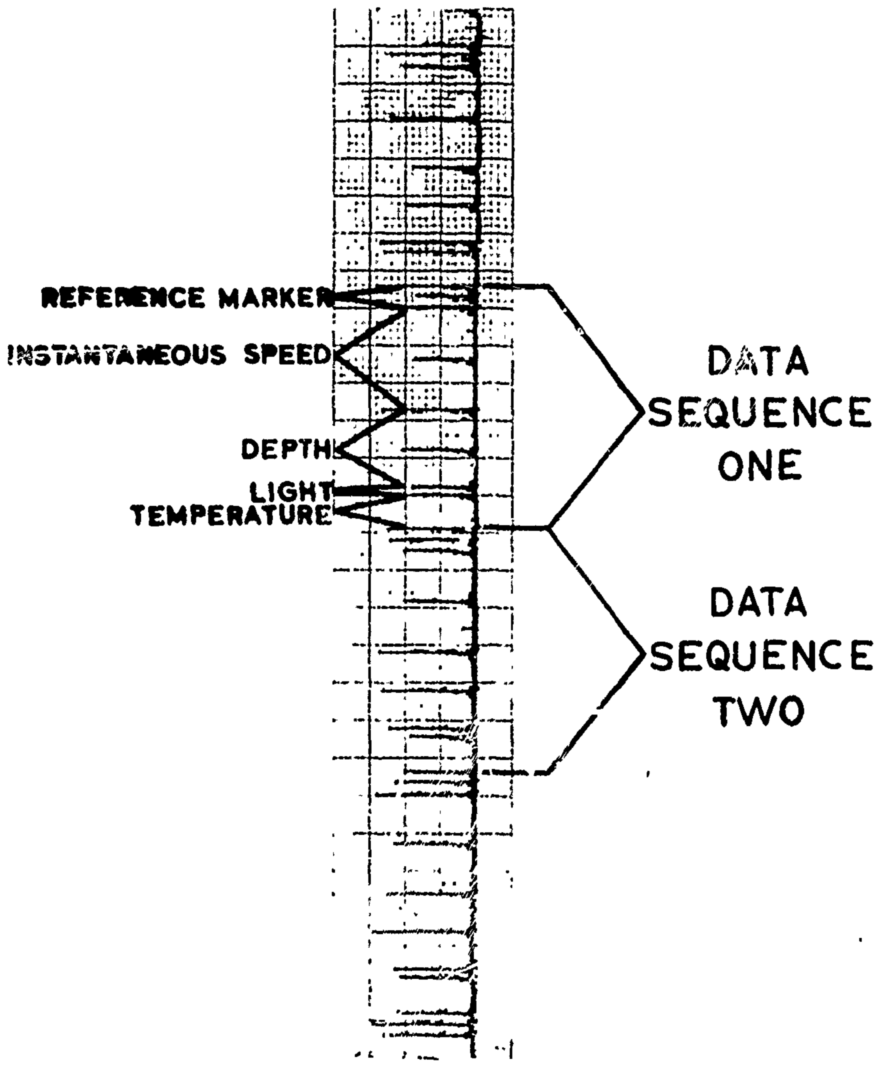


Figure 7. Data strip from an 8-channel transmitter (electronic multiplexer). On this particular unit (having 4 sensors) the reference marker, speed, and depth were wired to occupy 2 channels each. Recorded from an angel shark near Santa Catalina Island, California.

sequence and contains a fixed resistor of a value less than any sensor's minimum value. The circuit also contains a fail-safe system of high-resistance shunts and low-value resistors in series to be certain the unit will still operate and continue multiplexing despite a shorted or opened sensor circuit. This system will also allow the unit to continue transmitting (as a beeper) in the event of a failure in the multiplexer circuitry.

Electronic multiplexer (alternate function):

The Mark III electronic multiplexer can also be modified from its standard method (one interpulse interval/channel) of sequentially monitoring sensor status to a fixed time method (a predetermined number of seconds/channel) (Fig. 8). The manner in which the data is received in time blocks makes it easy to analyze when it is played through an oscillograph (Fig. 9) and also makes it possible for the receiver operator to note changes in each sensor value audibly. If the on time for each channel is long enough, e.g., 5 or 10 seconds, it is suitable for manual "stopwatch" decoding. To achieve immediate analysis, however, it is necessary to have a sufficiently long and clear transmission so that a full sequence can be received. With the standard electronic multiplexer a full data sequence is obtained in

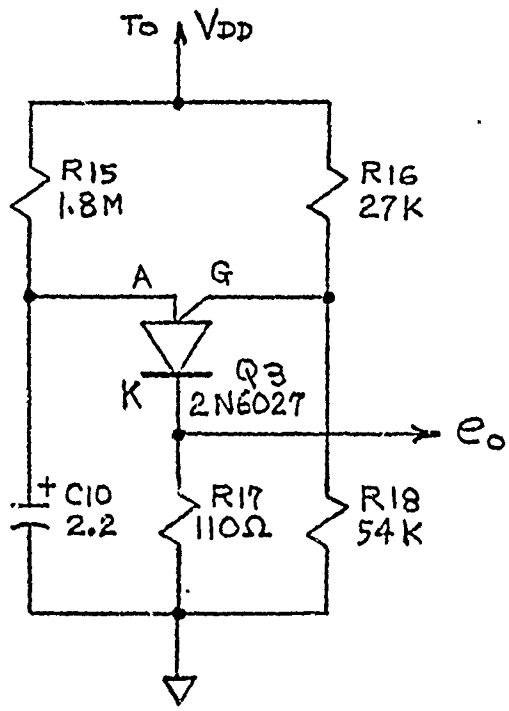


Figure 8. Schematic for electronic clock. This circuit may be used to clock the multiplexer sequential controller so that each channel will be sequentially sampled for a fixed time interval (in this case three seconds). Other time intervals may be selected by changing the values of C10 and R15. Connect e_o to pin 14 of IC-4 in place of wire from pin 4 of IC-1.

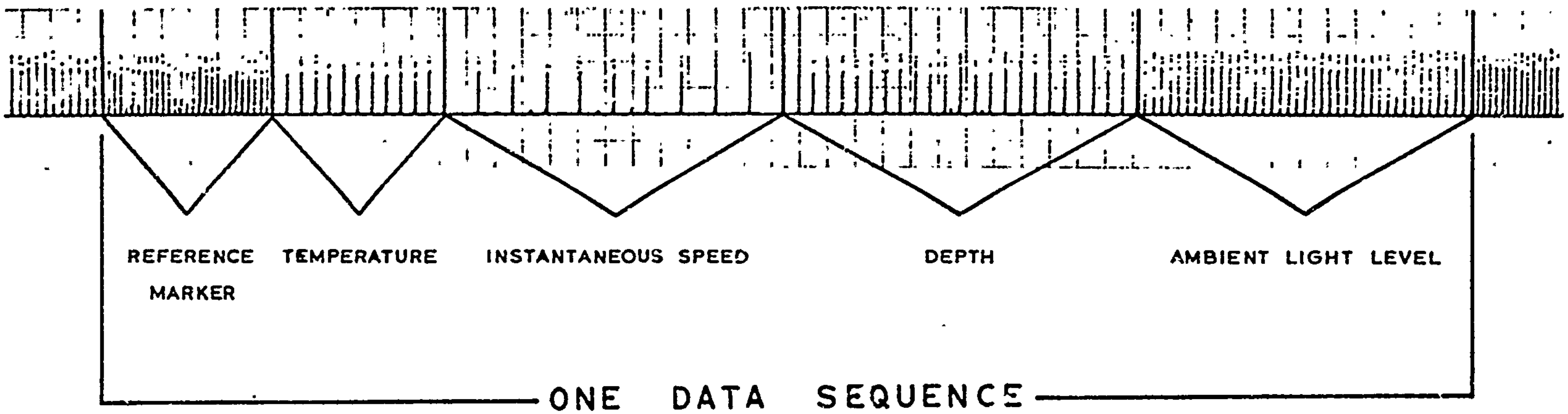


Figure 9. Data strip from an 8-channel transmitter with alternate-function multiplexer (controlled by electronic clock set for 3 sec.). On this particular unit, speed, depth, and light sensors were wired to occupy 2 channels each, thereby being monitored for 6 sec. each. Relatively long periods of time per channel make it easier to detect changes in sensor values audibly and allow manual "stopwatch" decoding of data.

approximately two to five seconds. Such rapid multiplexing, however, precludes manual "stopwatch" timing of each channel, but would be preferred when automatic methods of decoding and analysis are available and this method may be best when tracking at long distances or under marginal conditions.

Electromechanical commutator (earlier multichannel switching device):

Another method of expanding the single-channel transmitter to multichannel capability is to add a wiper-blade electromechanical commutator between the sensors and the pulse interval modulator. This approach was used while the electronic multiplexer was still under development and is described here because it functioned reasonably well, although it is the less preferred method.

The commutator consists of a small, low-drain motor (1.4 V., 10 ma) connected through a reduction gearhead (5,750 : 1) to a spring tension beryllium copper wiper blade (Fig. 10). The rotating wiper blade makes contact against a circular printed circuit board which has eight "pie-shaped" segments of copper on its surface. The segments are of two sizes, 20° for the marker channels and 50° for the data and calibrate-reference channels. The calibrate-reference channel and marker channels are connected to a fixed resistor of a value lower than that

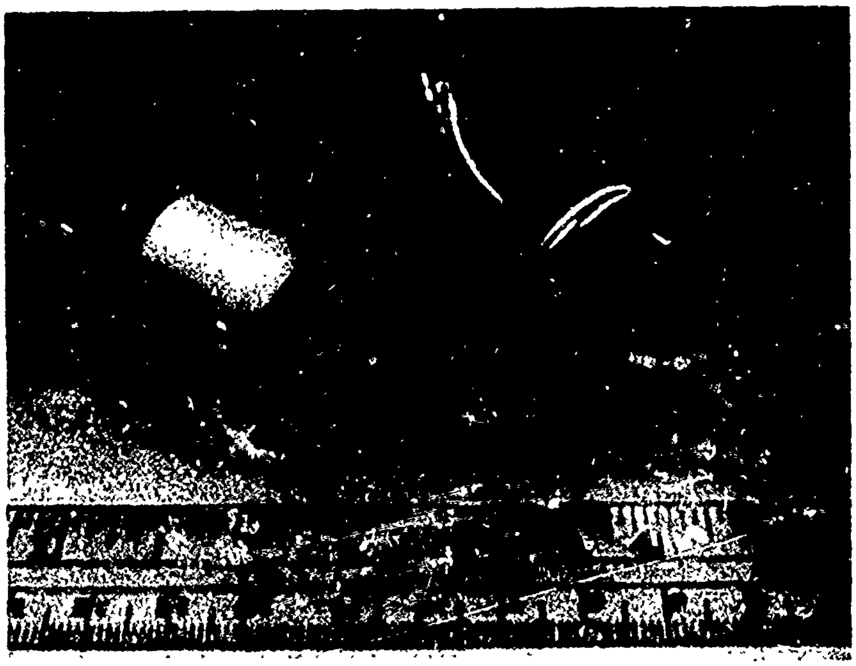


Figure 10. Electromechanical commutator which was used successfully while the present electronic multiplexer was being developed. The O-ring sealed plexiglas housing is opened to show the motor, gearhead, and wiper blade (right) and the segmented contact plate (left).

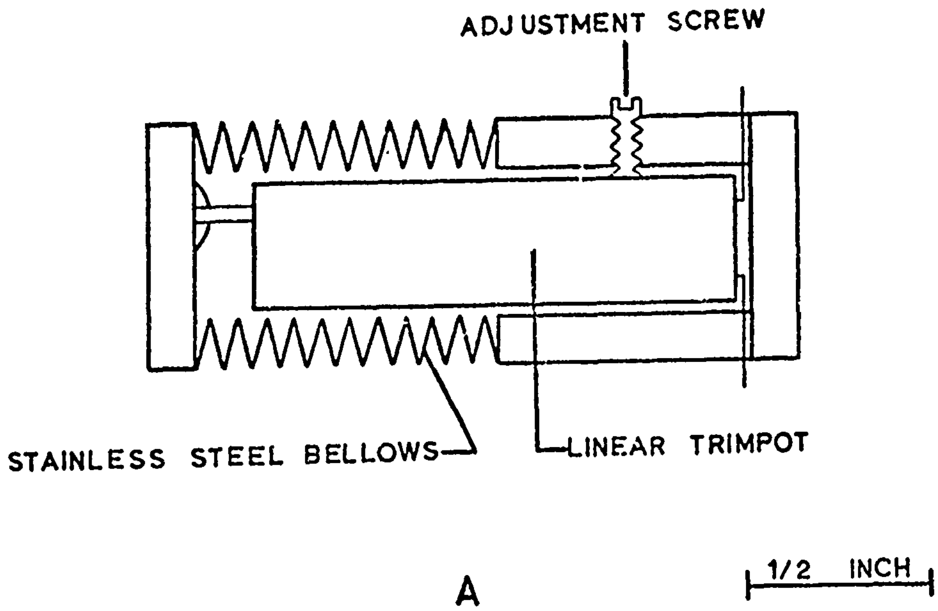
possible with any sensor. By having each of the sensor channels preceeded or followed by one of the three brief marker channels or the longer calibrate-reference channel the incoming data sequence can be easily identified. The wiper blade completes two revolutions per minute making each sensor channel and calibrate-reference channel approximately four seconds long. The entire commutator is enclosed in a pressure-resistant Plexiglas housing to which is attached a single 1.4 volt 750 mah mercury cell to power the unit and a magnetic reed switch to turn it on and off.

This method offers the advantages of time-block data but has the drawbacks of size (2 in. x 1 in. dia.), additional weight, extra battery cell, and the motor noise which might affect the behavior of the animal being monitored. This method, as with the alternate function electronic multiplexer, is most applicable to studies of parameters where rapid changes seldom occur in the time interval between successive samplings of a particular channel.

Sensor designs

Depth sensors (Fig. 11):

To convert depth to a resistance which can control the pulse rate of the transmitter it is first necessary to



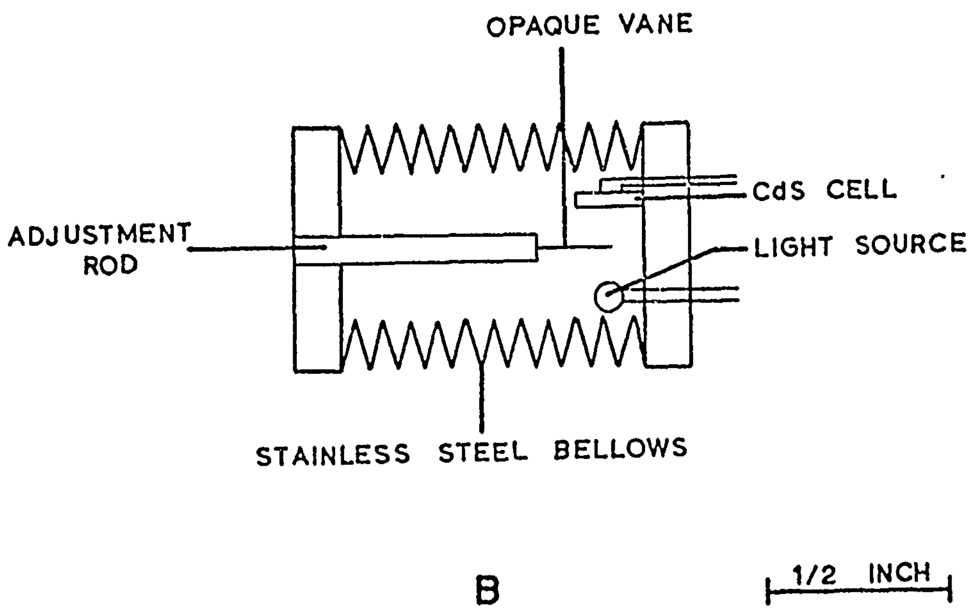


Figure 11. Depth sensors: (A) trimpot type, (B) light-photocell type. A variation of B without vane has photocell and light source mounted to opposite end caps.

convert pressure into mechanical movement. This was achieved by using bellows constructed of corrugated stainless steel. This mechanical movement was then converted into a resistance change by two basic methods.

Method (1) utilizes a linear-motion trimming potentiometer. By pulling the trimpot's slider to its most extended position its resistance is at a minimum value, and when the slider is fully inserted the resistance value is at its maximum. One end of the bellows is capped and sealed and the other end is fitted with a small tube in which the trimpot is placed. By attaching the trimpot slider to the bellows' endcap and carefully positioning the trimpot body in the tube the sensor can be adjusted to give a reading of 50 Kohms at the surface and increasing values of resistance as the unit is exposed to greater depths.

Method (2) employs photo-resistive cadmium sulfide cells which change resistance with the amount of light to which they are exposed. The photocell and a light source are attached to one end cap and are separated from each other by an opaque vane which is supported by the opposite end cap. The vane can be positioned by an adjustment rod until the photocell has a convenient starting value such as 50 Kohms. With this arrangement, as the bellows become more compressed (with an increase in depth) the vane

obscures more of the light source and the resistance of the photocell increases.

Three different types of light sources have been applied in the depth sensor and other sensors which also utilize photo-resistive cells. The most direct method was to use a 1.5 volt low-drain (10 ma) miniature light bulb. This was satisfactory but required an additional mercury cell as well as correction factors to compensate for the decrease in light output as the voltage dropped, especially at low operating temperatures. In an effort to obtain a constant light source not requiring batteries or correction factors a laboratory prototype depth sensor was constructed using a high-output Betalight. These are phosphor-coated quartz bulbs which contain radioactive tritium gas. While these produce essentially constant illumination (half-life 7 years), the cost of each plus the legal restrictions resulted in our rejecting their use. The system we are presently using incorporates very-low-drain light emitting diodes (L.E.D.'s) powered by zener-diode-regulated voltage from the main battery.

The depth sensors are calibrated in a pressure chamber by recording the resistance change as the pressure is increased. The resulting graph can be used in conjunction with a calibration graph for the transmitter on which resistance and pulse rate is plotted, to give the relationship

of depth to pulse rate. Depending on the bellows used, these sensors can cover various depth ranges. Two we presently use cover depths of 0 to 300 feet and 0 to 600 feet.

Swimming-speed sensors (Fig. 12):

Two types of sensors have been used successfully to determine shark swimming speeds. The earlier type is essentially a floating tilt indicator mounted on a rotating hinge which makes it possible for the sensor to maintain the proper attitude despite any pitching, yawing or rolling of the swimming shark. The float section contains five carbon resistors and four micro-mercury switches which are installed at angles which cause them to close cumulatively as the unit is tilted from vertical. As each switch closes it introduces another resistor into a parallel circuit. When the float is in an upright position all switches are open and the transmitter is presented with a base resistance of 250 Kohms. As the float is forced to increasing angles by the swimming shark, the resistance decreases in increments of 50 Kohms until it is nearly horizontal and the sensor is at its minimum value of 50 Kohms.

The second type of speed sensor uses the light-photocell method to obtain a resistance change. In this sensor, the opaque vane which separates the photocell from the light

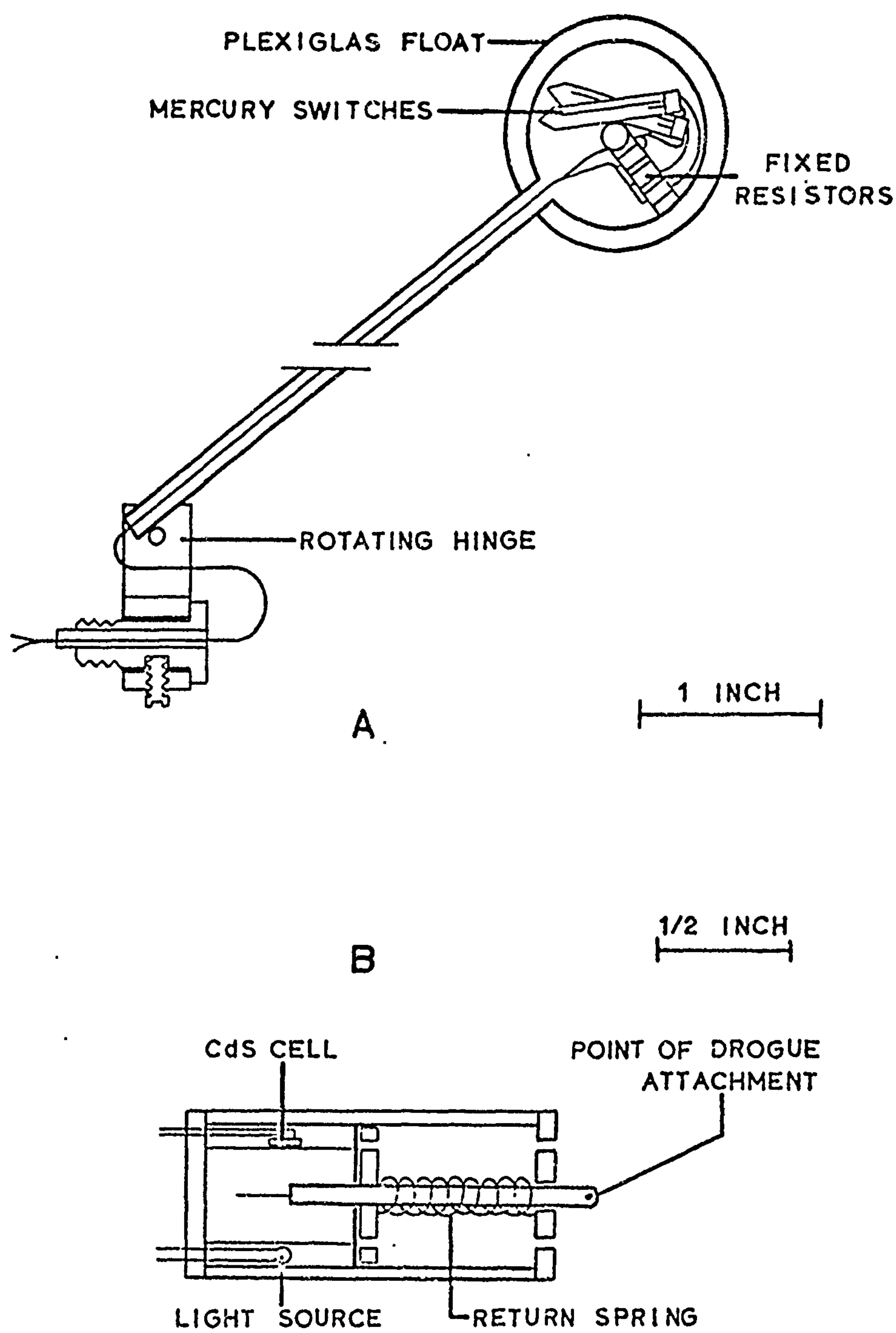


Figure 12. Swimming-speed sensors: (A) tilt-indicator type, air filled; (B) drouge type, free flooding with opaque baffles to keep interior dark. A much smaller version of B utilizes the spring itself (without vane) to vary the light reaching the photocell.

source is controlled by a spring-mounted rod connected to a drogue by means of a short monofilament line. As the shark increases its swimming speed the drogue pulls the vane from between the light and photocell which causes a decrease in sensor resistance. When the shark slows its swimming speed, the vane moves inward.

Both types of sensors (which measure approximately 0 to 5 MPH) are calibrated by mounting them on a testing platform which is pulled through the water at various constant rates over a premeasured distance. As this is being done the resistance of the sensor is monitored to provide data for a graph of resistance related to swimming speed.

Compass sensors (Fig. 13):

Three types of light-photocell sensors have been constructed to telemeter the instantaneous compass heading of the shark. For these sensors the light source acts on a rotating drum which is attached to a magnet mounted on pivots. In one type the drum is a transparency gradient ranging from opaque to clear. In a second type the photocell and light source are on the same side of the drum which is painted to form a reflective gradient ranging from dark to light. As the compass drum rotates, a particular light level and hence resistance can be correlated with a specific

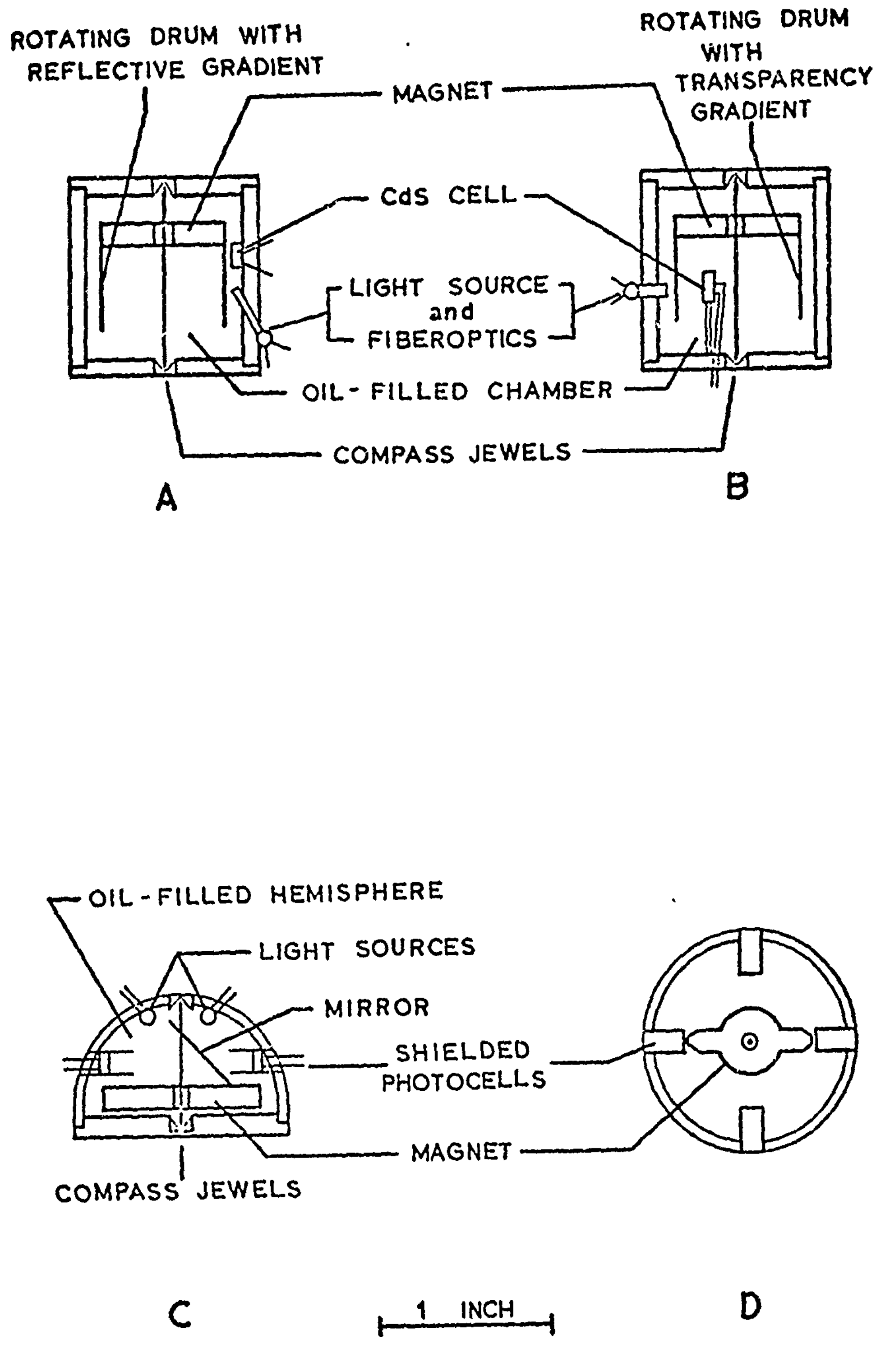


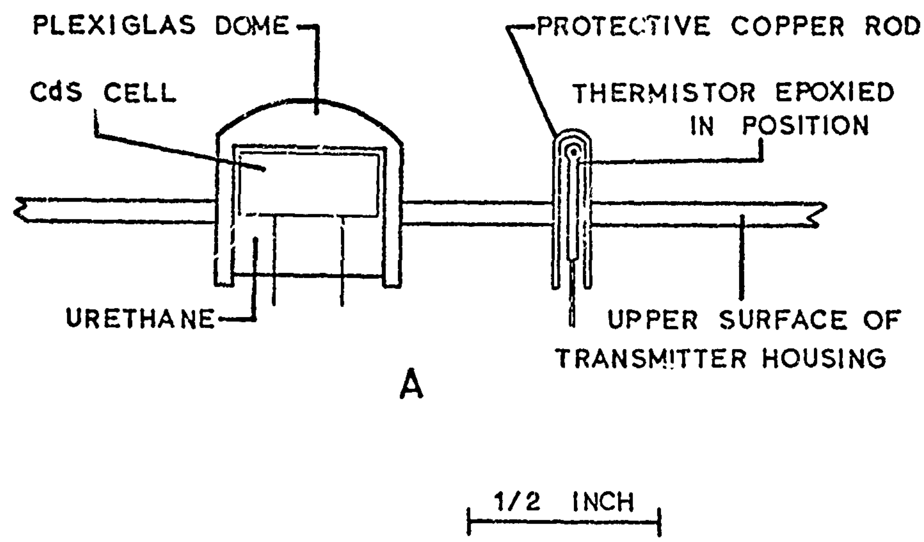
Figure 13. Compass sensors: (A) reflective type; (B) transparency type; (C) four-channel type, side view; (D) four-channel type, bottom view

compass heading. Both of these methods, however, have a small sector of ambiguity at the junction between the light and dark areas where intermediate light-level readings occur.

A new four-channel design which gives readings without ambiguity contains four photocells mounted around the magnet at four points of the compass. The light source is adjusted above the magnet pivot in such a way that a beam of light strikes a mirror on the magnet which aims the ray in a fixed direction with respect to the magnet. For any compass direction, the light shines primarily on one of the four photocells, each of which is connected to its own transmitter channel. With this four-channel method it is possible to tell at a glance the approximate direction in which the shark is heading. The compass sensor is positioned in the transmitter housing so that it is away from ferric materials such as the ba ery case. Because of possible magnetic interference by various transmitter components the compass sensor is always calibrated after it is installed within the transmitter housing.

Light sensors (Fig. 14):

This sensor was incorporated to determine the level of ambient light at the shark. It consists of a cadmium sulfide



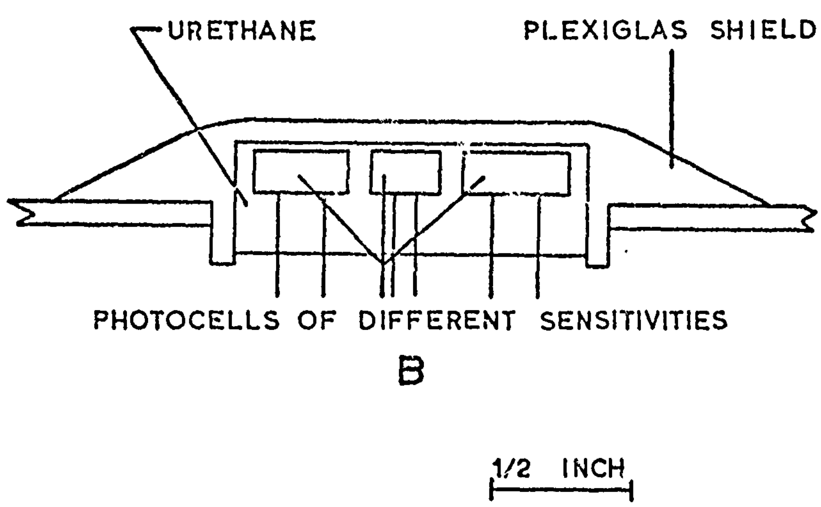


Figure 14. Ambient light and temperature sensors: (A) section of transmitter housing showing positioning of photocell type light sensor and temperature sensor, (B) photocell-array type light sensor.

photocell embedded in a Plexiglas protective dome mounted on the top of the transmitter. The photocell selected has its peak spectral response in the blue-green range, has adequate temperature stability and has a resistance range compatible with the transmitter circuitry. Photocells can be chosen to detect light levels at critical times such as at dawn and dusk transition periods or very sensitive ones can be used to distinguish differences between nights of full moon or new moon. For some applications a bank of photocells is used to cover a wide range of illumination levels, in which case each photocell occupies one sensor channel. For the light sensor calibrations, the graphs provided by the photocell manufacturers are used.

Temperature sensor (Fig. 14):

A temperature sensor is used for telemetering the temperature of the water through which the shark is swimming. It consists of a conventional thermistor epoxied inside of a copper rod which protects it and yet assures rapid heat conduction. The sensor is external to the transmitter housing for rapid sensing of sudden temperature changes such as those occurring when the shark passes through a thermocline.

Packaging

The housing for the transmitter (Fig. 15) is a 6-inch long polyvinyl chloride (P.V.C.) tube, 1.3 in. in diameter. The transmitter and multiplexing circuitry is laid out on four or five disc-shaped printed circuit boards (Fig. 16) which are held together by an insulating rod. After assembly, the electronic components are sprayed with a protective lacquer-like liquid to prevent shorting in the event of seawater incursion into the transmitter housing. The front end of the tube is closed with a slush-molded latex boot which is held in position by a wrapping of electrical tape. It is necessary to have one endcap flexible so that the internal depth sensor can function properly and also to reduce the possibility of sea water entering the system because of a pressure differential. The entire unit is filled with castor oil to assure proper acoustic coupling of the PZT element to the sea water. In an effort to exclude all air bubbles from the unit a vacuum hose is placed over the back end cap filling port as the oil is introduced. This aluminum end cap is epoxied to the tube, and contains the threaded filling hole in addition to holes for the velocity and temperature sensors. In some units the temperature sensor protrudes from the top of the housing along with the ambient light sensor(s). The

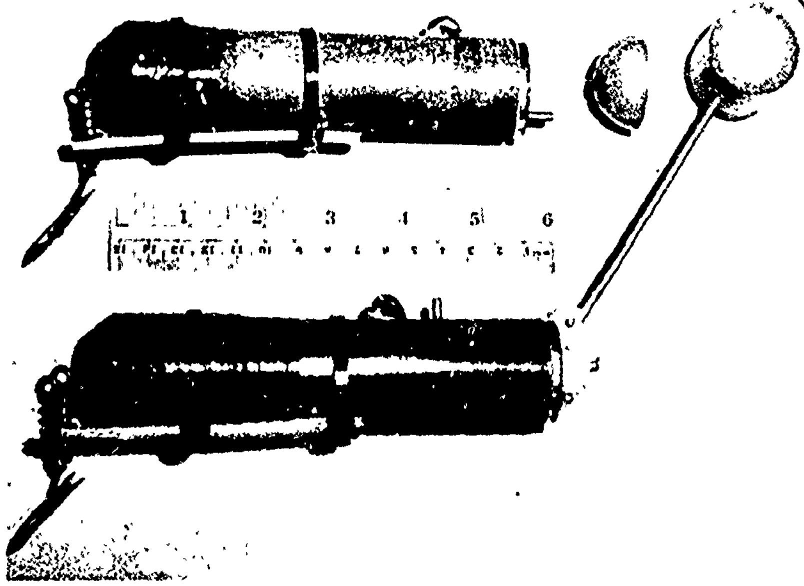


Figure 15. Multichannel transmitters: external view showing base plate, attachment barb, and magnesium link. Top, unit with drouge-type speed sensor. Bottom, unit with tilt-type speed sensor.

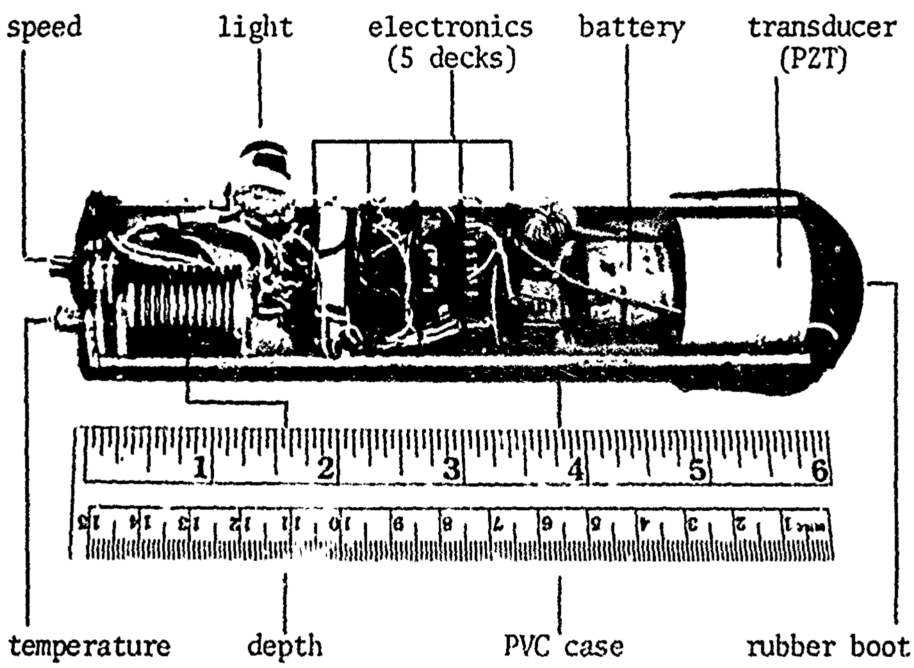


Figure 16. Multichannel transmitter: cut-away view showing internal components of an 8-channel unit with depth, speed (drouge-type), light, and temperature sensors.

depth sensor is sometimes placed within the PZT cylinder.

The mercury battery is modified by removal of its metal case to prevent its crushing with depth due to the air entrapped between individual cells. Each cell is then coated with melted paraffin to prevent accidental shorting. The battery is connected to the transmitter by wire leads soldered to the metal strips which are spot welded to the cell cases. The transmitter is actuated by a normally-on magnetic reed switch which is glued to the inside of the PVC tube. To start the transmitter, it is only necessary to remove a magnet temporarily taped to the outside of the housing.

Application and recovery

To facilitate transmitter attachment the unit is fixed to a thin aluminum or plastic base plate by means of three nylon zip straps. The base plate is attached to the shark by using a stainless-steel barb (modified AIBS dart tag, Floy FH-69). After experimenting with various fixed and hinged barbs it was found that this thin stainless-steel barb with flexible stainless-steel connecting wire worked best. The transmitter is affixed to the shark by using an applicator pole which supports the unit and positions the barb so it can be attached in one quick thrust (Fig. 17). The implantation takes less than a second and can be performed equally well by a scuba diver

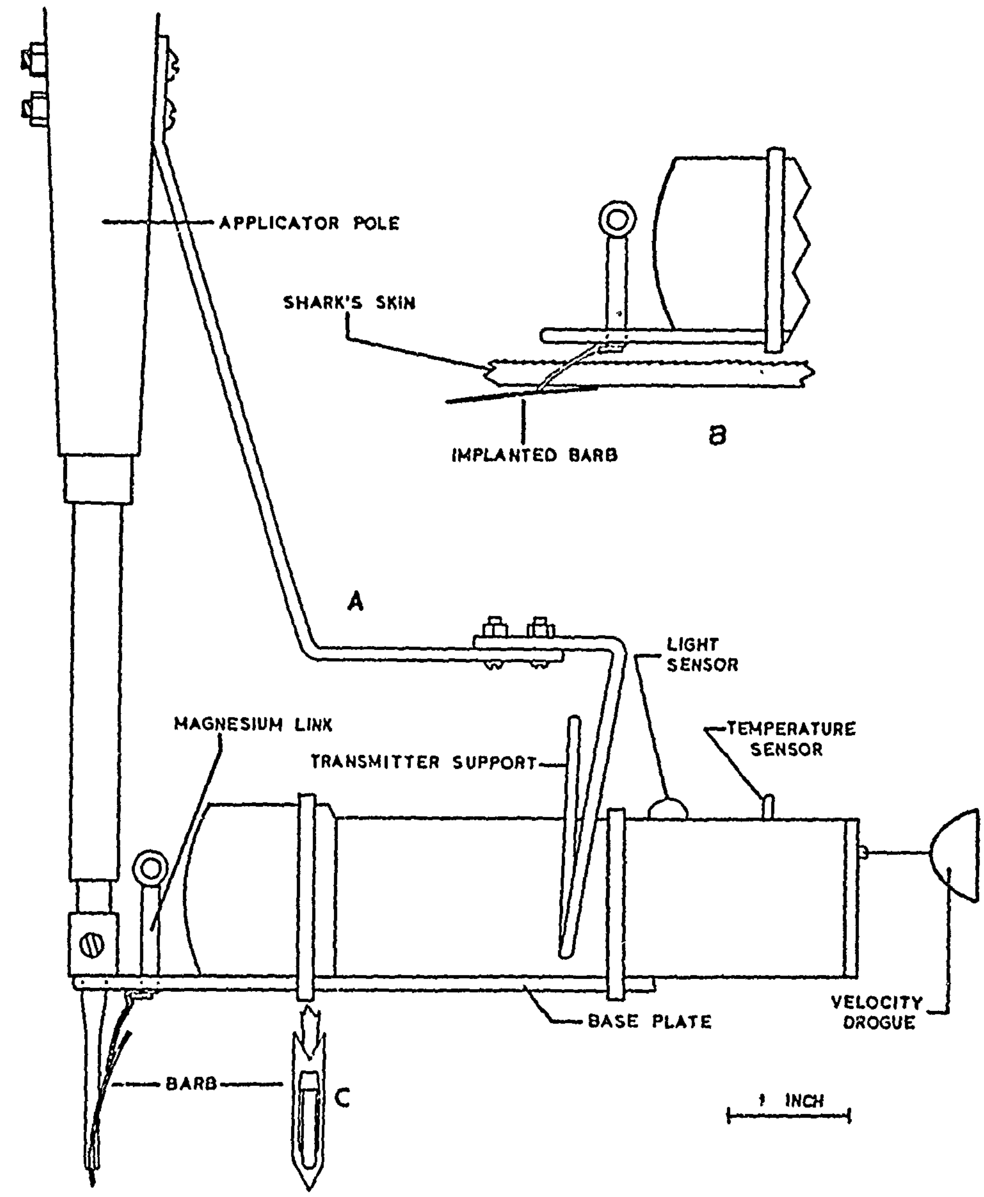


Figure 17. Apparatus used to attach transmitters to sharks. (A) applicator pole with transmitter in place, (B) position of stainless-steel barb after implantation, (C) front view of barb.

working underwater or a person in the boat (Fig. 18) who has attracted sharks within reach. Other possible methods of attachment include bringing the shark aboard and suturing the unit directly to the shark or feeding the transmitter to a shark by concealing it in a piece of bait.

Although the transmitters can be considered expendable if necessary, there are obvious advantages in retrieval of the units after each usage. Two recovery methods have been successful. The first and most direct method of recovery is location and capture of the shark by scuba divers with a directional sonic receiver. This approach is especially useful for recovering transmitting packages from sedentary sharks, such as angel sharks, which have settled in water less than 200 feet deep. This method also has the advantage of providing additional biological data such as the length, weight, and sex of the individual in addition to making it possible to analyze stomach contents.

The second method of recovery involves the use of a magnesium break-away link which erodes away in seawater at a predetermined rate, eventually separating the transmitter from the shark. Since the transmitters are negatively buoyant, some flotation is necessary to be certain they will rise to the surface after release. A syntactic foam float is attached to the transmitter and the break-away

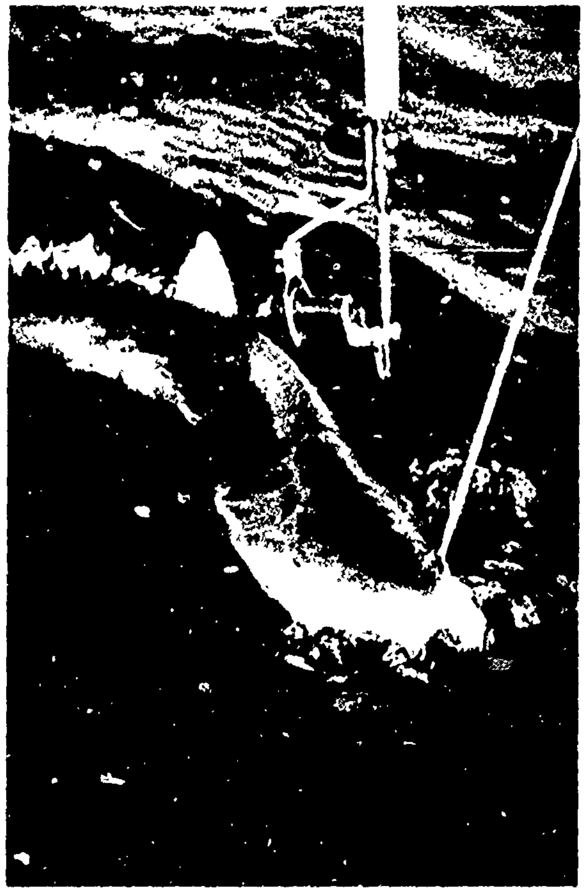


Figure 18. Applying transmitter to blue shark, Prionace glauca, baited to boat while shark bites bait cannister (attached to rope shown in photo).

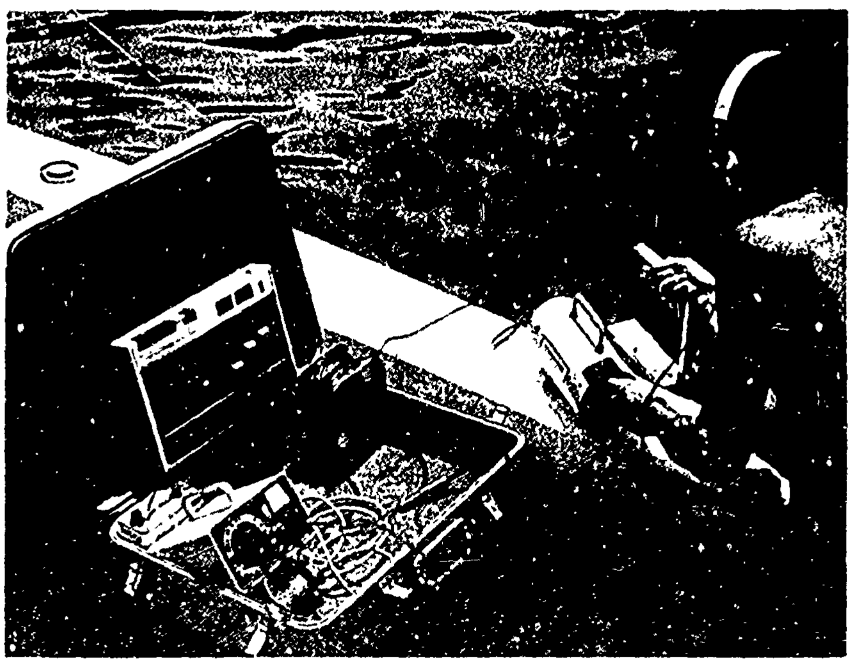


Figure 19. Personnel in boat with receiving gear: Smith-Root receiver with omnidirectional hydrophone (on long cable), stereo cassette data recorder, DuKane receiver (on gunwale) with staff-mounted directional hydrophone being held in the water.

link is placed between the holding barb and the transmitter. Using this method, a high percentage of recoveries can be achieved. Under a fixed set of conditions the releasal time can be predicted to within five percent. Erosion time can vary considerably with water temperature and flow rate, however, and the releasal time for an inactive shark in deep, cold water can be as much as twice that for an active shark in shallow, warm water.

Receivers and hydrophones

Two commercially manufactured receivers are used for monitoring the shark's behavior (Fig. 19). A Smith-Root TA-25 ultrasonic receiver equipped with an omnidirectional hydrophone of our design is usually kept on for the entire tracking operation to be certain contact is maintained. A DuKane model N15A235 receiver equipped with its staff-mounted directional hydrophone is used during most data recording, for obtaining directional headings, and when working near maximum range. For tracking and transmitter retrieval by a scuba diver the DuKane receiver is used in its underwater configuration.

The hydrophones which we use with the Smith-Root receiver are constructed using PZT elements identical to those used in the transmitters. The omnidirectional hydrophones contain a PZT element and its support in an oil filled,

cylindrical rubber boot. The directional hydrophone is similar but placed at the focal point of a 15-inch diameter foam-neoprene lined parabolic reflector. This reflector makes it possible to receive weaker signals because of concentration of the acoustic energy and shielding of much of the ambient noise. Because of the reflector's size and weight, including pan and tilt controls and gimballed support, it is attached to the side of the research boat. This arrangement works well under calm conditions but with considerable wave action the motion of the boat makes it almost impossible to maintain accurate parabola positioning. Although the reflector-type directional hydrophone was used routinely prior to obtaining the DuKane system, it is presently not used very often.

Using the DuKane receiver (10dB down at ± 500 Hz) with its built-in directional hydrophone we have detected the Mark III unit at distances of up to 3.2 miles. Good quality data recordings, however, are usually obtained at distances between 1.5 and 2.0 miles depending on sea conditions. Using the Smith-Root receiver (6dB down at ± 1.5 KHz) equipped with an omnidirectional hydrophone the transmitter could usually be detected at distances up to 3/4 mile, and under excellent conditions up to 1.5 miles. The only times

there is difficulty in receiving clear data are when the shark moves into rocky areas where there are concentrations of snapping shrimp or when there is sufficient wind to cause white caps. When the sea is rough the hydrophone plunges up and down with the movement of the boat and the waves slap against the hull, both of which cause interference with clear reception of the signal. There is greater difficulty in tracking the shark under these conditions and it takes longer to analyze recorded data because of the time required to differentiate between data pulses and noise.

Another condition which can drastically vary the amplitude of the received signal is when the shark is located very near the surface in rough water (with large waves) when the receiving hydrophone is also near the surface. When this occurs, as it has while tracking blue sharks, the direct line of acoustic transmission is often poor or absent, and only a weaker diffused or bottom-reflected signal is received. This presents difficulty in tracking the shark and often requires that the hydrophone be lowered well below the surface, e.g., about 40 feet.

Data recording and analysis

With single-channel units analysis requires only a stopwatch. The time required for ten clicks is measured

and the sensor value then read directly from a calibration graph. With multichannel units with sufficiently long fixed-time multiplexing, e.g., 5 or 10 sec., similar field analysis can be performed.

With one pulse interval/channel multichannel transmitters, however, channel switching is rapid, making it necessary to record the signal and then later measure the distance between peaks to determine each interpulse duration. It was found that the best way to do this is to record the incoming field data directly on a magnetic tape and, back in the lab, play the recorded data into an oscillograph. This method makes it possible to store large quantities of data and yet selectively analyze the most pertinent information as desired. A two-channel cassette tape recorder is used with one channel exclusively for data and the other for verbal notes such as times and locations.

The presently used measuring and analyzing procedure is very time consuming. The distance between peaks on the oscillograph recordings is measured by eye with the aid of a magnification retical. With data coming in at an average rate of three bits per second, 260,000 for one 24-hour tag, it is practical to analyze only a small fraction of the total potential data by this method. Procedures for automatic data reduction, e.g., electronic demultiplexing

and computer analysis, are currently under development.

To process the incoming signal so that it is of a high enough quality so it can be analyzed by automatic means, a signal discriminator and conditioner is also currently being developed. This device produces a brief tone burst each time it detects an incoming signal of the proper amplitude, frequency, and pulse length. When this is added to the present system it should be possible to make near-perfect recordings even in areas of high ambient noise.

DISCUSSION AND FUTURE PLANS

With the system we have described it is now possible to monitor continuously the behavior of any large aquatic animal for several day-night cycles. The primary difficulty in acquiring several days of continuous data involves the physical endurance of the tracking personnel. Our transmitters can function for a week, but the practical limit due to fatigue on the small research boat, often in rough water, has usually been reached at the end of one day-night cycle. At the present we prefer to have four topside researchers for each tagging operation who alternate duty time and rest time in teams of two. On several occasions 24-hour tracks have been performed by only two operators with no significant rest periods. The ideal situation, of course, would be to have sufficient personnel

for longer tracking sessions with a more favorable duty-rest ratio when at sea. One possibility (even with limited manpower) would be several days of intermittent monitoring alternated with rest periods. Such an approach would be especially feasible when working with inshore species which have a limited home range.

The question arises as to what effect the tagging procedure has on the animal being studied, both at the time of barb implantation and after carrying the unit for several hours or days. One comparison which has yet to be made is the effect on behavior of various methods of transmitter attachment. One method is to capture the shark and bring it on board the boat and then carefully suture the unit to the skin. Although the initial handling would be quite traumatic to the animal, there would probably be minimum discomfort after it is returned to the water. It is unknown, however, how long the shark needs to recover from this initial handling. The alternative method, which we presently utilize, is a brief, relatively atraumatic implantation to an unrestrained shark in the water. The possible disadvantage in this case depends on the degree of irritation caused by the remaining presence of the attachment barb. Based on observations to date, it does not appear that the behavior

of the animals is seriously altered for more than a few seconds after barb implantation. For example, blue sharks, Prionace glauca, baited to the boat for tagging were seen to resume feeding immediately after being tagged (Fig. 21). Angel sharks, Squatina californica, (Fig. 20) were noted to swim away after being tagged at speeds slower than that often recorded during routine activity later that night. Evidence for non-disrupted behavior after several days is one tagged angel shark with a full stomach when captured during the recovery of a transmitter.

The only observation of modified behavior which has been noted thus far was the attraction of two untagged blue sharks to a bright orange transmitter float carried by another blue shark. Such intraspecific interactions might modify an animal's behavior but the extent of this interference will have to await further investigation. The additional drag of the float itself might affect the shark's behavior to some degree. The obvious advantages to using a float for recovery are the financial and construction-time savings. Although the float eliminates any weight on the shark (one ounce positive buoyancy) it adds to the overall drag and inertia of the transmitter. If the float is eliminated, there is a reduction in drag and inertia but the shark has to contend with a 3.5-ounce negatively buoyant transmitter, and the researchers have to contend

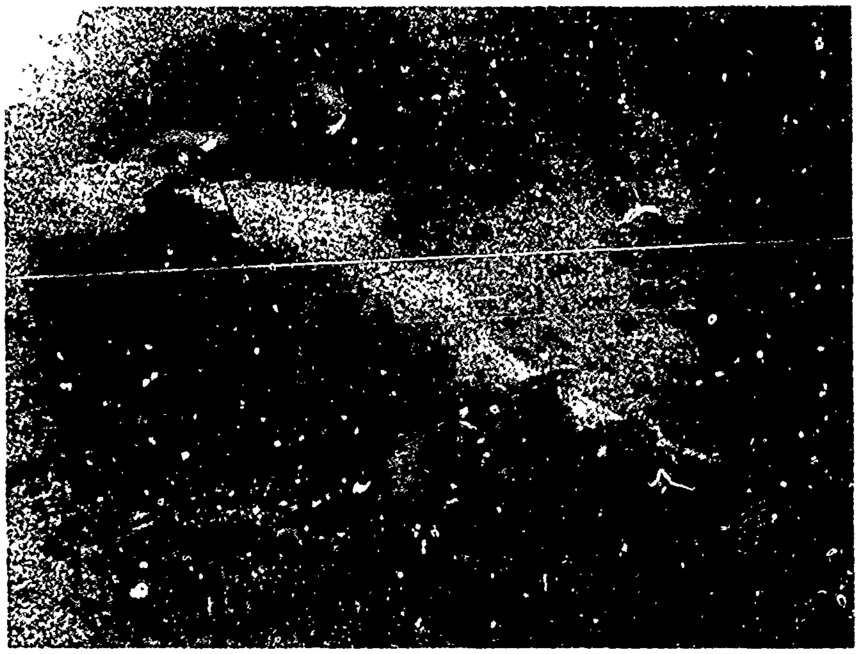


Figure 20. Angel shark, Squatina californica, tagged with transmitter with tilt-type speed sensor. Shark shown resting on sandy bottom which is normal habitat for this species.

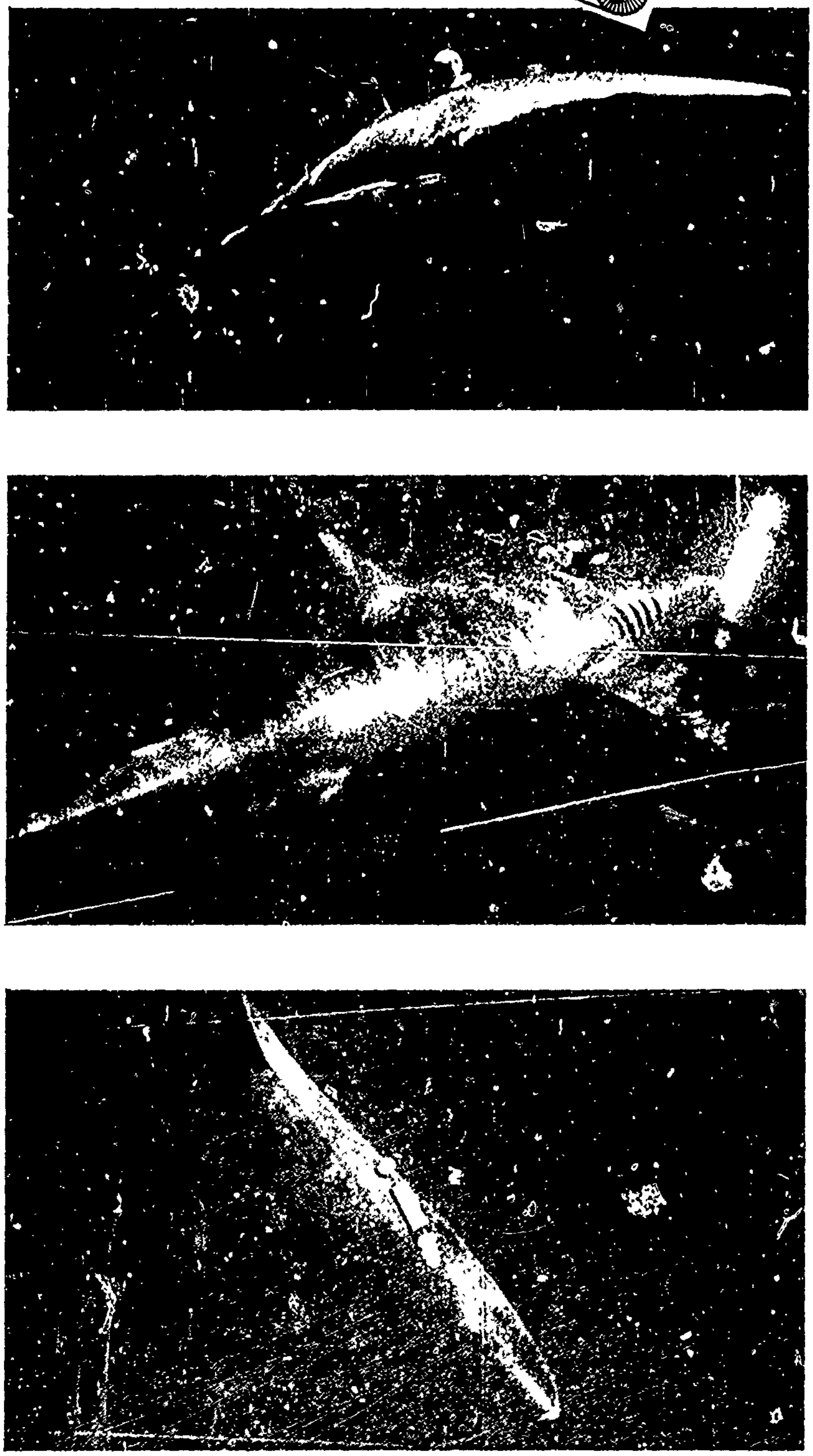


Figure 21. Blue sharks, Prionace glauca, tagged with transmitters. Center photo shows large individual returning to bait cannister immediately after tag application. Bottom photo shows transmitter with a drouge-type speed sensor.

with the loss of a transmitter each tracking session, unless a recovery can be made using scuba.

Although this report discusses primarily multichannel transmitters there are instances when single-channel units may be preferred. Such a situation would be when a researcher wants to monitor one particular parameter which can change value rapidly and briefly, but only infrequently, e.g., jaw opening or sudden acceleration during feeding. With either type of multiplexing, but especially fixed time/channel, it would be possible to miss such data by being on the wrong channel. A single-channel transmitter allows the researcher to detect audibly any change immediately. This also makes it possible to monitor the shark continuously but only record the important changes as they occur.

Reliability during use at sea

During the developmental program to date, 23 test tracking missions of from 4 to 28 hours each have been conducted using the Mark III transmitters on sharks at sea. Of these, 19 (83%) were considered successful in that contact was maintained and data received throughout or nearly throughout the desired duration of the mission. There were 3 unsuccessful missions attributed to actual or apparent

failure of the transmitters[1]. Another failure involved eventual loss of contact with a weakened signal from an improperly functioning unit[2]. In no case was a properly operating transmitter lost because of inability to track its signal with the receiving system described[3].

Of the described sensors, the more recently designed drouge-type speed sensor (7 missions) and the photocell-type depth sensor (10 missions) have been 100% reliable to date. A few earlier designs failed during otherwise successful missions: One trimpot-type depth sensor and two

[1]One unit on a blue shark was lost after 7 hours of clear reception when signal abruptly ceased (reason unknown). One unit on an angel shark transmitted only very intermittent and erratic pulses, then was lost after several hours (suspected cause, shorting due to water incursion or intermittent contact at broken solder joint). Unit on another angel shark became erratic after 1 hour, then ceased (unit later recovered, had water incursion into circuitry). Two of these circuits were not given the moisture-proof spray presently used.

[2]After 11 hours of good reception, signal weakened greatly and doubled frequency to about 80 KHz, signal finally lost after 17 hours (suspected cause, abnormally low battery voltage possibly due to shorting by sea water).

[3]After 5 hours of tracking, one blue shark was lost for 4 hours, then relocated and successfully tracked for the rest of the mission. Another blue shark mission was abandoned when deep hydrophone was lost (cable severed by shark bite) and tracking could not be maintained with remaining surface hydrophone.

tilt-type speed sensors leaked due to faulty sealing. One trimpot-type depth sensor (plexiglas case) and two potted thermistor assemblies cracked, possibly from high pressure and thermal-mechanical stress due to different materials. It was found that several photocell light sensors were ruined by chemical action of a potting compound (polyester resin) on the photoresistive material.

The stainless-steel attachment barbs have been completely reliable. Once properly implanted, the barbs always kept the transmitters on the sharks throughout the tracking missions.

The magnesium link-float recovery system has been 93% reliable to date, i.e., of 16 units being tracked at the expected time of release, 15 reached the surface, were sighted, and recovered. The reason that one unit failed to surface is unknown, but possibilities include damage to the float or entanglement in lines, kelp, or other debris.

The few transmitter problems encountered to date are believed primarily attributable to imperfections in construction or assembly rather than in basic design. Reliability of operation of any given unit is dependent on how carefully and skillfully it was built. Many opportunities for flaws in construction exist in the many parts

and connections in a hand-made Mark III multichannel transmitter. It should be realized that, in addition to some ability in electronic trouble-shooting, proper construction requires many specialized skills and techniques in such things as machining, soldering, gluing, potting, etc., and these techniques are usually acquired best through trial-and-error experience. Persons inexperienced in these things can easily underestimate the amount of effort necessary, at least initially, to produce the transmitters described. The best way to achieve maximum reliability, if one can afford it, is to contract out the construction and testing of the units to companies experienced in such work.

Future improvements in the system

Although the Mark III telemetry system at the described stage of development has proven quite useable for biological study of sharks at sea, it should not be considered an end product in need of no further improvement. Many of the handmade transmitter components, although already the result of much evolution in design, could certainly be improved further. The technology of construction, assembly, and packaging could be considerably improved -- especially if handled by companies experienced in such techniques, instead of by the biologists themselves.

One desired improvement in any system of this type is a reduction in size of the transmitter to reduce its possible effects on the tagged animal and to extend its usefulness to smaller species. A step in this direction is micro-miniaturization of the circuitry through the use of hybrid integrated circuit construction. Although initial tooling costs would be relatively high (about $1,000 for the Mark III, 8-channel unit) the cost per unit would be reasonable ($100), the savings in time and labor would be great, and circuit reliability would be increased. A high percentage of recoveries, such as we have experienced thus far, contributes to the feasibility of using more expensive construction such as hybrid circuitry.

Sensors of the future can undoubtedly be made smaller through design improvement and more careful machining. It would also be useful to develop additional kinds of sensors for behavioral events such as jaw movement, fin posture, tail beats, etc. Sensors can also be devised for various physiological parameters, or for monitoring internal conditions of the transmitter itself, e.g., battery voltage.

A highly accurate device for timing transmitter releasal is under development utilizing electronic E-cell timers. This will make possible more specific planning of tracking mission durations, alleviating the present uncertainties

occurring with the magnesium breakaway links. Addition of a transponding capability to the Mark III crcuitry is being considered. This will make possible such operations as triggering of identifiable return pulses (for calculation of shark-to-boat distance), command switching of multiplexing mode, or command release of transmitter from shark.

Improved tracking and data receiving would undoubtedly be possible with better shipboard receiving gear (narrower bandwidth, higher sensitivity). Also under consideration are submersible recording or relaying stations (for inshore operations) and automatic tracking devices (for pelagic operations). Such systems would alleviate the present manpower fatigue problem, making possible longer-term behavioral monitoring with less personnel. In addition to the noise rejection device mentioned earlier, a shipboard demultiplexer and data read-out system is now being developed. One final goal is to have complete computer reduction and analysis of data recorded during long-term continuous monitoring.

Biological studies

A pilot behavioral study of the Pacific angel shark, *Squatina californica*, has been conducted using the Mark III transmitters. Units were applied by scuba divers to sharks

at Santa Catalina Island, California. Nine successful one-diel-cycle trackings (13-25 hrs.) were completed; four with single-channel units (depth or swimming-speed sensor), and five with multichannel units (depth, swimming-speed, temperature, and light). Transmitters were recovered in seven of these cases. Data indicated basically nocturnal behavior. Daytime locomotor activity was low, with swimming activity increasing at the approach of dusk and often continuing through dawn. Nightly forays were up to six miles in length, at depths of 90 to 330 feet, often ending near the same area where begun. Examples of single-channel and multi-channel data from the angel shark are shown in Figs. 22 and 23. A detailed description of this work is given by Standora (1972b).

A telemetric study of the behavior of blue sharks, Prionace glauca, is presently being conducted. To date, two single-channel and ten multichannel operations have been conducted, with transmitter recoveries in eight cases. Sharks baited to the boat are tagged in the pelagic environment several miles off Catalina Island. Most individuals appeared relatively unaffected by transmitter attachment; newly tagged sharks often stayed around the boat orienting to the bait cannister. All sharks remained offshore during daylight hours, usually at shallow depths, but most moved in close to the Island at dusk. They typically stayed near the Island for several

hours, swam along the shoreline at depths varying from shallow to deep (0 to over 325 feet), then gradually moved back out to sea. An example of multichannel data from a blue shark is shown in Fig. 24. Full disclosure of the results of this study will be given by Sciarrotta (in prep.).

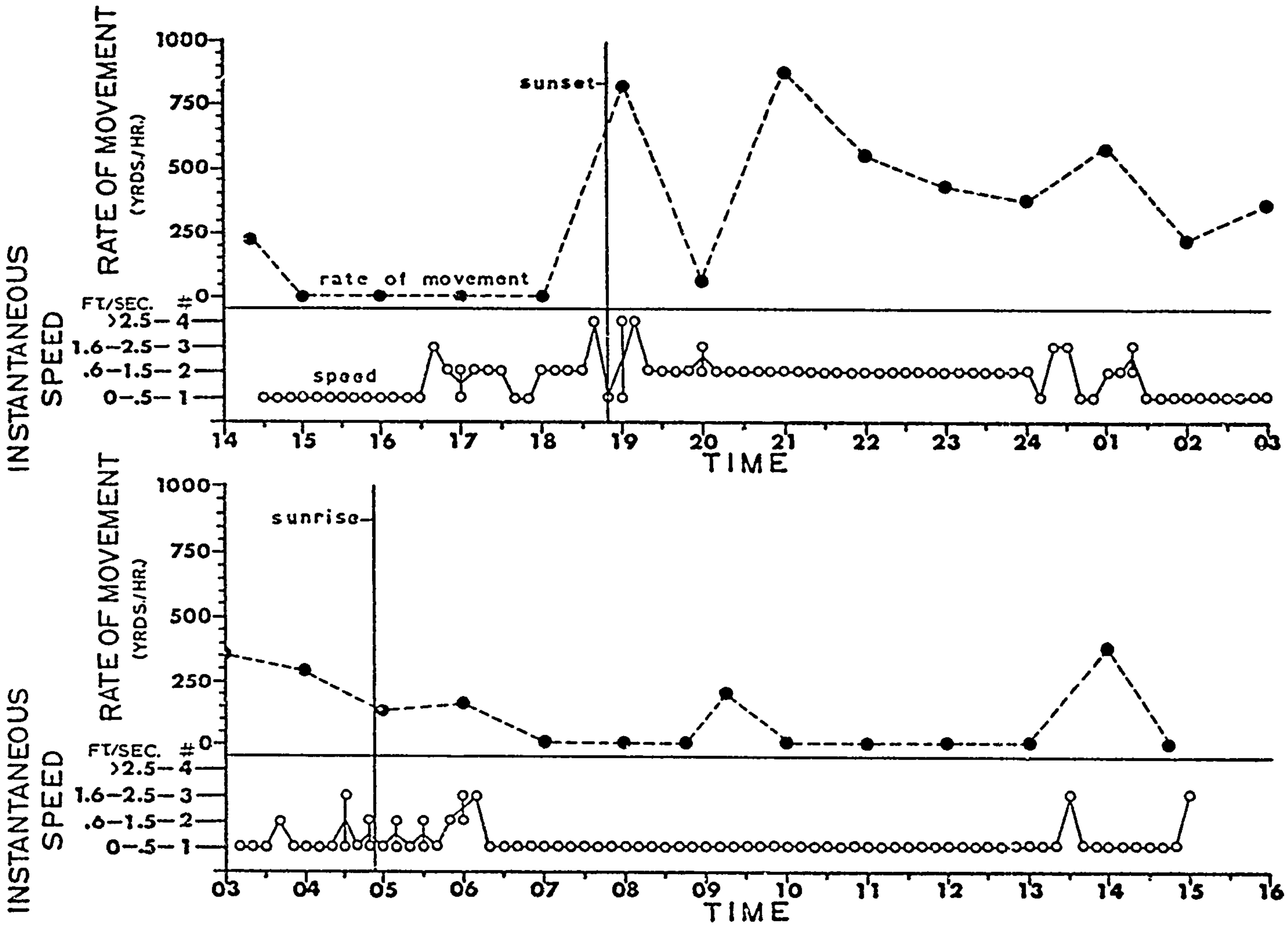


Figure 22. Example of single-channel data from an angel shark. Telemetered swimming-speed data recorded at 10-minute intervals for approximately 25 hours. Rate of movement (calculated from shark-location data) plotted every hour.

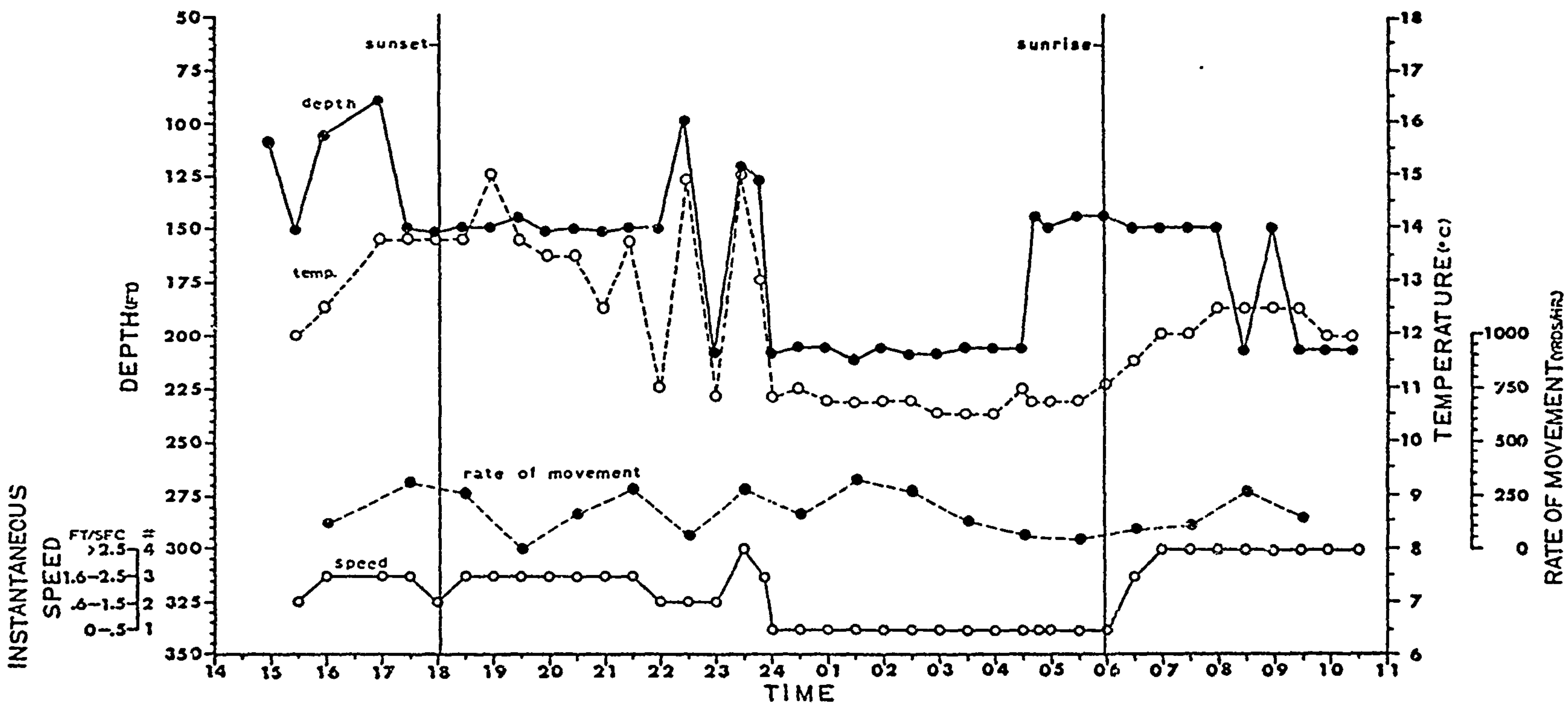


Figure 23. Example of multichannel data from an angel shark. Telemetered data from depth, temperature, and swimming-speed sensors recorded at 30-min intervals.

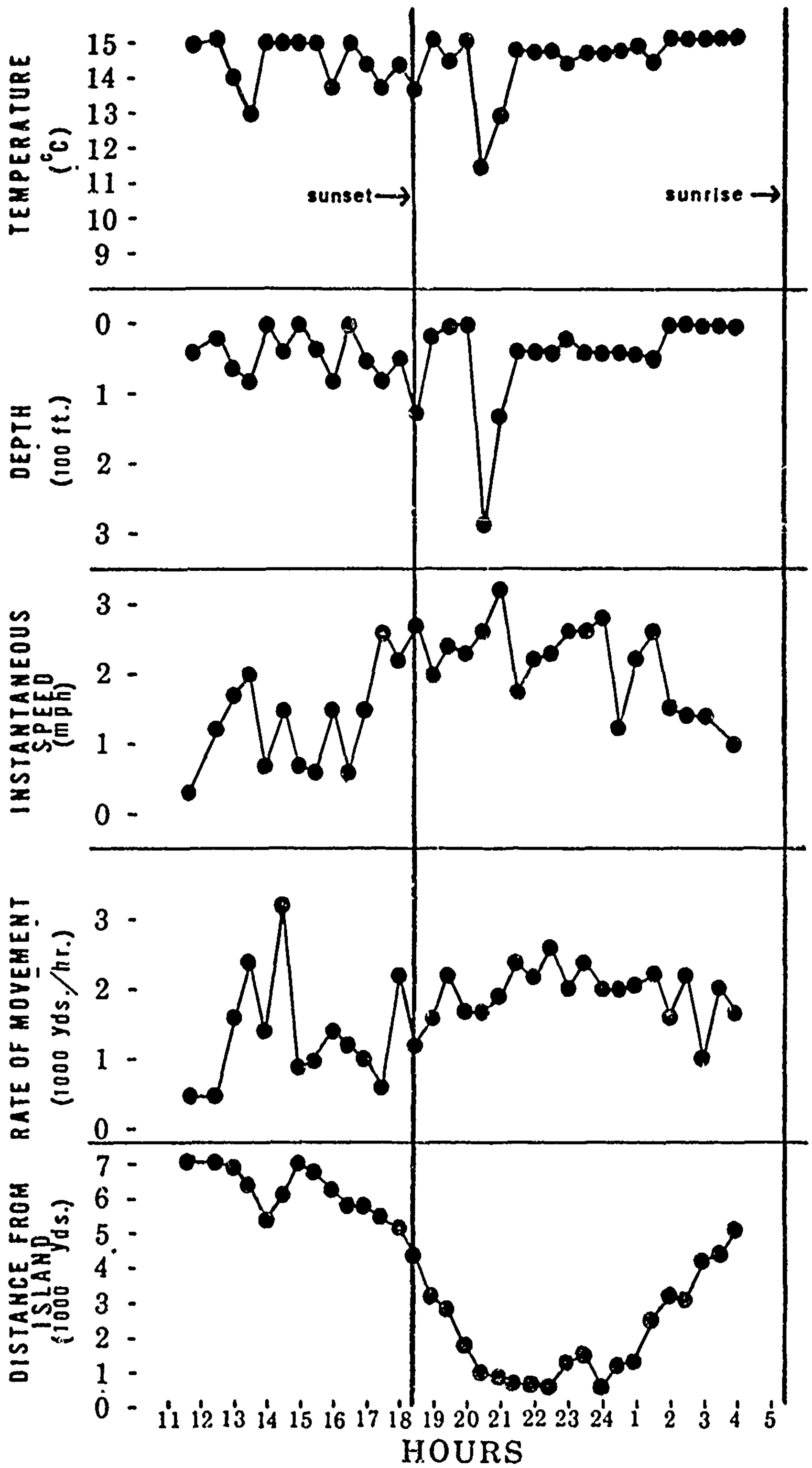


Figure 24. Example of multichannel data from a blue shark. Note the correlation between depth and temperature, the increased swimming speed after sunset, and the close approach to the island shore in early evening. Data recorded at 30-min intervals for approximately 17 hours.

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APPENDIX

The following information has been included to assist those interested in constructing the Mark III transmitters and/or sensors described. Components or materials not readily obtainable are indicated with a superscript corresponding to one of the suppliers listed at the end.

Transmitter cost

Approximate cost of parts for one complete single-channel transmitter with a photocell-type depth sensor (bellows 281) ....$ 42.

Approximate cost of parts for one complete 8-channel transmitter with photocell-type depth sensor (bellows 281), drouge-type speed sensor, compass sensor, light sensor, and temperature sensor..................$ 75.

Construction time

Approximate construction and calibration time (for a graduate student in biology) for (1) and (10) complete single-channel units with depth sensors, 6 and 15 days respectively; for (1) and (10) complete 8-channel units with sensors described above, 19 and 41 days respectively.

Estimated time to assemble (1) and (10) 8-channel transmitters using pre-constructed sensors and hybrid circuitry, 4 and 12 days respectively.

Parts list

I. Transmitter electronic components:

a. Basic Mark III transmitter (single-channel)

(2) Darlington power transistors, GE D40C1.....$ 2.25

(1) PZT ceramic transducer[1].................... 9.65

(2) integrated circuits, RCA CD4001AE.......... 3.54

(1) toroid, Ferroxcube 266CT 125 (3E2A) 28T.... .75

(1) cup-core transformer, Ferroxcube 140 8P-L00-3B7.................................. 1.00

Resistors (1/8 w.): (2) 220K, (2) 10K, (1) 390K, (1) 39K and (1) 3.9K (1/4 w.).................. 1.40

Capacitors: (3) .005 mfd, (1) .039 mfd, (1) 300 mfd, (1) 2.2 mfd, (1) 10 mfd, and (1) 200 pf... 4.00

(3) diodes.................................... .85

$23.44

b. 4-channel multiplexer

(1) integrated circuit, RCA CD4016AE...........$ 3.60

(1) integrated circuit, RCA CD4022AE........... 7.65

Resistors (1/8 w.); (1) 2.2 meg, (1) 22K and (1) 10K...................................... .60

$11.85

c. 8-channel multiplexer

(2) integrated circuits, RCA CD4016AE..........$ 7.20

(1) integrated circuit, RCA CD4022AE........... 7.65

Resistors (1/8 w.): (1) 2.2 meg, (1) 22K and (1) 10K...................................... .60

$15.45

d. Electronic clock

(1) programmable unijunction transistor, GE U13T1...................................$ 1.10

Resistors (1/8 w.): (1) 51 ohm, (1) 54K, (1) 27K and (1) 1.8 meg............................ .60

(1) 2.2 mfd capacitor......................... .60

$ 2.30

e. Electro-mechanical commutator

(1) commutator motor[2], 1.4 v. Micro-Mo.........$10.00

(1) gear head[2], Micro-Mo 5750:1 reduction...... 3.50

Wiper blade, circuit board, Plexiglas, etc...... 1.00

$14.50

II. Sensors:

a. Depth (trimpot type)

(1) stainless-steel bellows[3], type 401.........$11.50

(1) linear motion trimpot[4], type 3049L-1-105... 6.98

Plexiglas, epoxy, etc.......................... .75

$19.23

b. Depth (light-photocell type)

(1) stainless-steel bellows[3], (0-300' range) type 401......................................$11.50

or (1) beryllium copper bellows[3], (0-600' range) type 281...................................... 9.06

(1) light emitting diode, Sprague type 150..... .85

(1) photoconductive cell[5] Vt 732............... .95

Aluminum, Plexiglas, epoxy, etc................. .75

(Type 281) $11.61

(Type 401) $14.05

c. Swimming-speed (tilt type)

(2) plastic hemispheres.......................$ 2.00

(4) mercury switches, Micro Switch # AS419A.... 14.00

(5) resistors (1/4 w.)......................... 1.00

Plexiglas, epoxy, copper tube, etc............. 1.00

$18.00

d. Swimming-speed (drouge type)

(1) Stainless steel spring.....................$ .35

(1) light emitting diode, Sprague type 150..... .85

(1) photoconductive cell[5], VT 901............. .95

Plexiglas, brass rod, drogue, etc.............. .75

$ 2.90

e. Compass (4-channel type)

(1) plastic hemisphere	$ .35
(2) brass pivots	1.00
(2) jewel bearings[6]	1.00
(4) photoconductive cells[5], VT 901	3.80
(2) light emitting diodes, Sprague type 150	1.70
(1) compass magnet	3.00
Plexiglas, mirror, resin, etc	.75
	$11.60

f. Temperature

(1) thermistor probe[7], type 51A11	$ 1.65
Copper rod, resin, etc	.30
	$ 1.95

g. Light

(1) photoconductive cell[5], VT 721H	$ .95
or (3) photoconductive cells[5], VT 82L, VT 721H and VT 322	2.85
Plexiglas, resin, etc	.40
(1 photocell)	$ 1.35
(3 photocells)	$ 3.25

III. Packaging and application components:

(1) magnesium link[8]	$ .14
(1) P.V.C. tube 1 1/4" O.D. by 5 1/2" long	.05
(1) tag applicator[9], Floy FH 69	1.50
(1) attachment barb[9], Floy FH 69	.10
(1) syntactic foam float[10], SH-12 material	4.00
Anhydrous castor oil[11], Plexiglas, baseplate, electrical tape, etc.	1.00
	$ 6.79

IV. Receiving and analysis equipment:

(1) Smith-Root[12], receiver, TA-25..............$525.00

(1) Dukane receiver[13], type N15A235............1995.00

(1) paper oscillograph[14], TR-711............... 495.00

(1) stereo cassette tape recorder, Allied Electronics SCT-2B............................$119.00

(1) stop watch.................................. 20.00

Suppliers

1. Channel Industries, 839 Ward Drive, Santa Barbara, California
2. Micro-Mo Company, Zurich, Switzerland (via Wilshire Model Center, 1304 Wilshire Blvd., Santa Monica, California)
3. Robertshaw Controls Co., Fulton Sylphon Division, Knoxville, Tennessee
4. Bourns, Inc., Instrument Division, 6135 Magnolia Ave., Riverside, California
5. Vactec, Inc., 2423 Northline Industrial Blvd., St. Louis, Missouri
6. Richard H. Bird & Co., Inc., 1 Spruce Street, Waltham, Massachusetts
7. Victory Engineering Corp., 128 Springfield Ave., Springfield, New Jersey
8. Oceanetics International, 9941 S.W. 126 St., Miami, Florida
9. Floy Tag and Manufacturing, 2909 N.E. Blakeley, Seattle, Washington
10. Emerson and Cumming, Inc., 609 West 182nd Street, Gardena, California
11. Baker Castor Oil Co., 5585 East 61st Street, Los Angeles, California
12. Smith-Root Laboratories, 129 1st Avenue West, Seattle, Washington
13. Dukane Corp., 2900 Dukane Drive, St. Charles, Illinois
14. Techni-rite Electronics, Inc., Techni-rite Industrial Park, Warwick, R.I.